Galactic Astrophysics

From Planets to Galaxies

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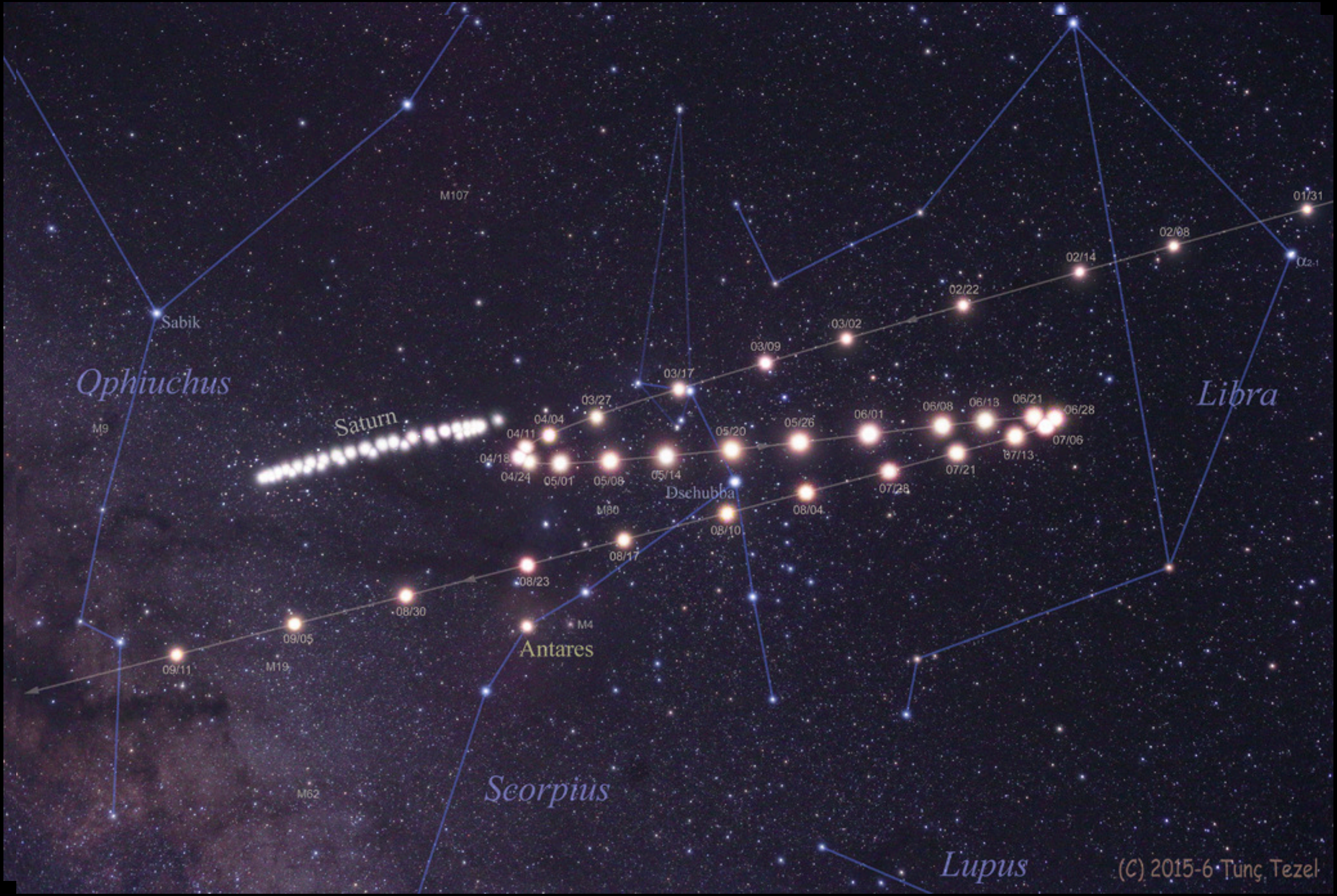
Questions We'll Cover

- Crash course: history of astrophysics
- How do we measure the distance to celestial objects?
- What does our local stellar and galactic neighborhood look like?
- How do stars work, and what can they tell us about physics?
- Star death: what happens when the fuel runs out?
- Black Holes and Neutron Stars

Studying the Universe

https://apod.nasa.gov/apod/ap160915.html

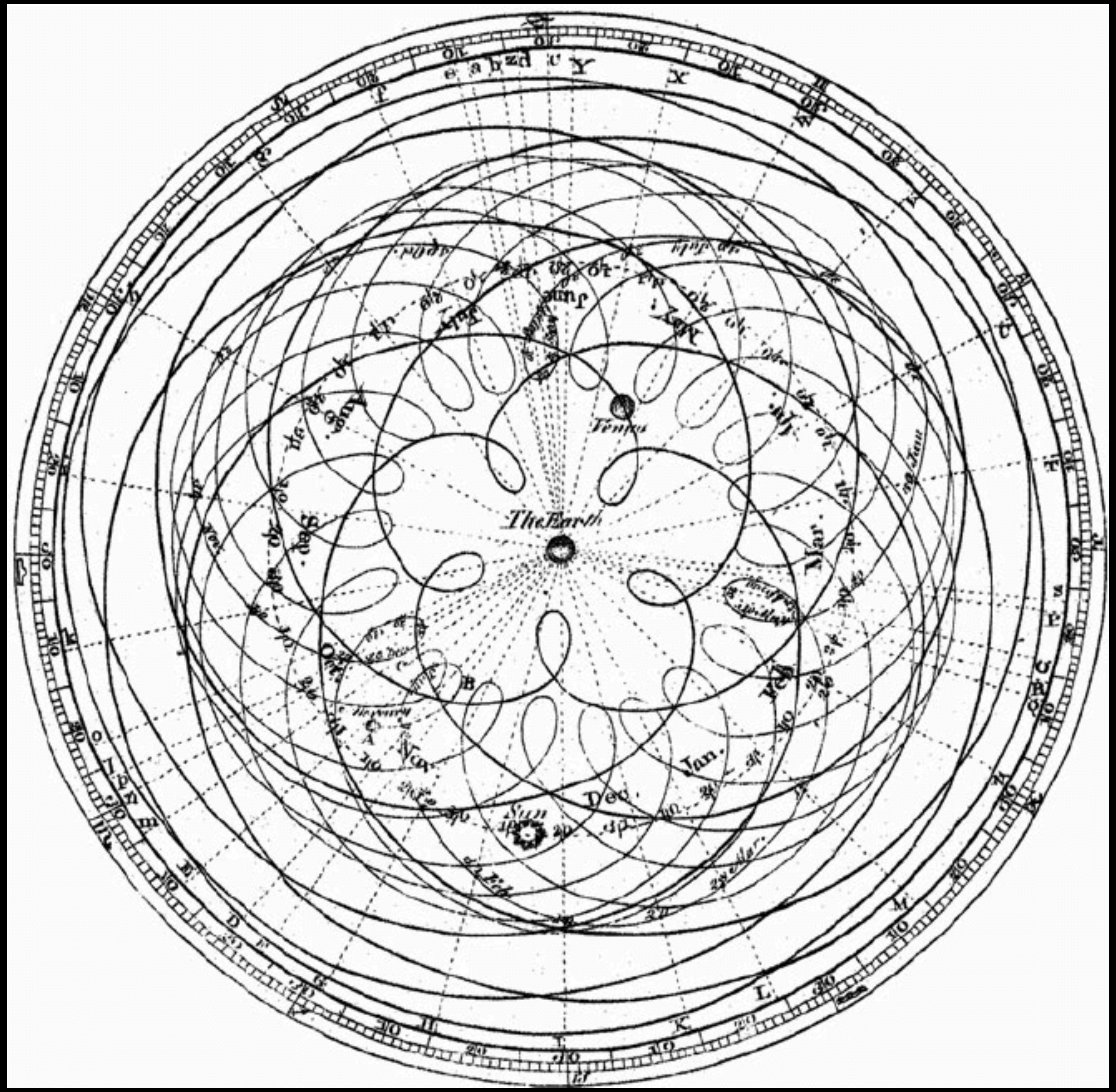


Ptolemaic Epicycles

Ptolemy to Brahe

Observing the Solar System

- Ptolemy's universe (2nd Century CE)
  - All bodies fall to the center of the universe
  - All motion is circular
  - Complex retrograde behavior accomplished using epicycles



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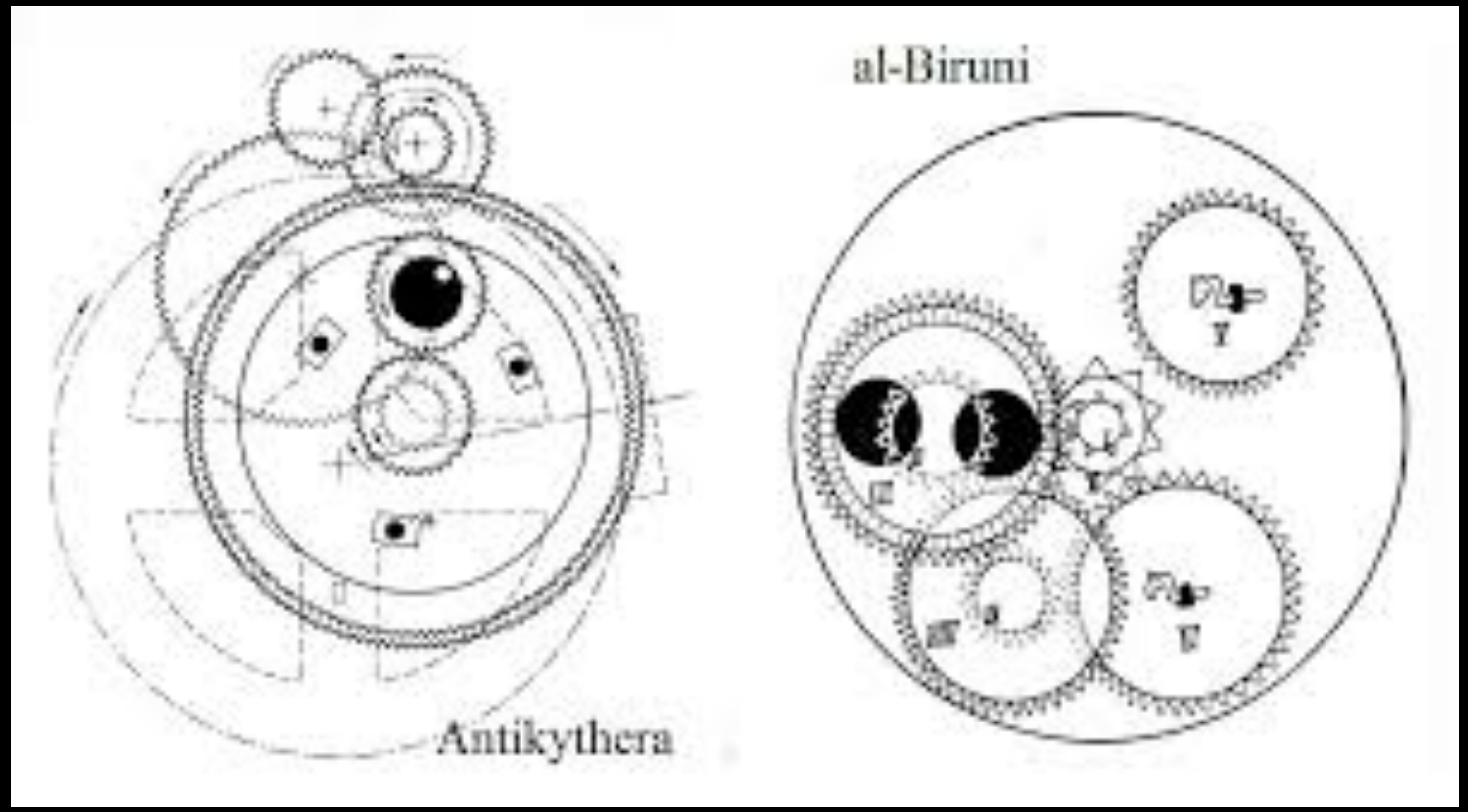
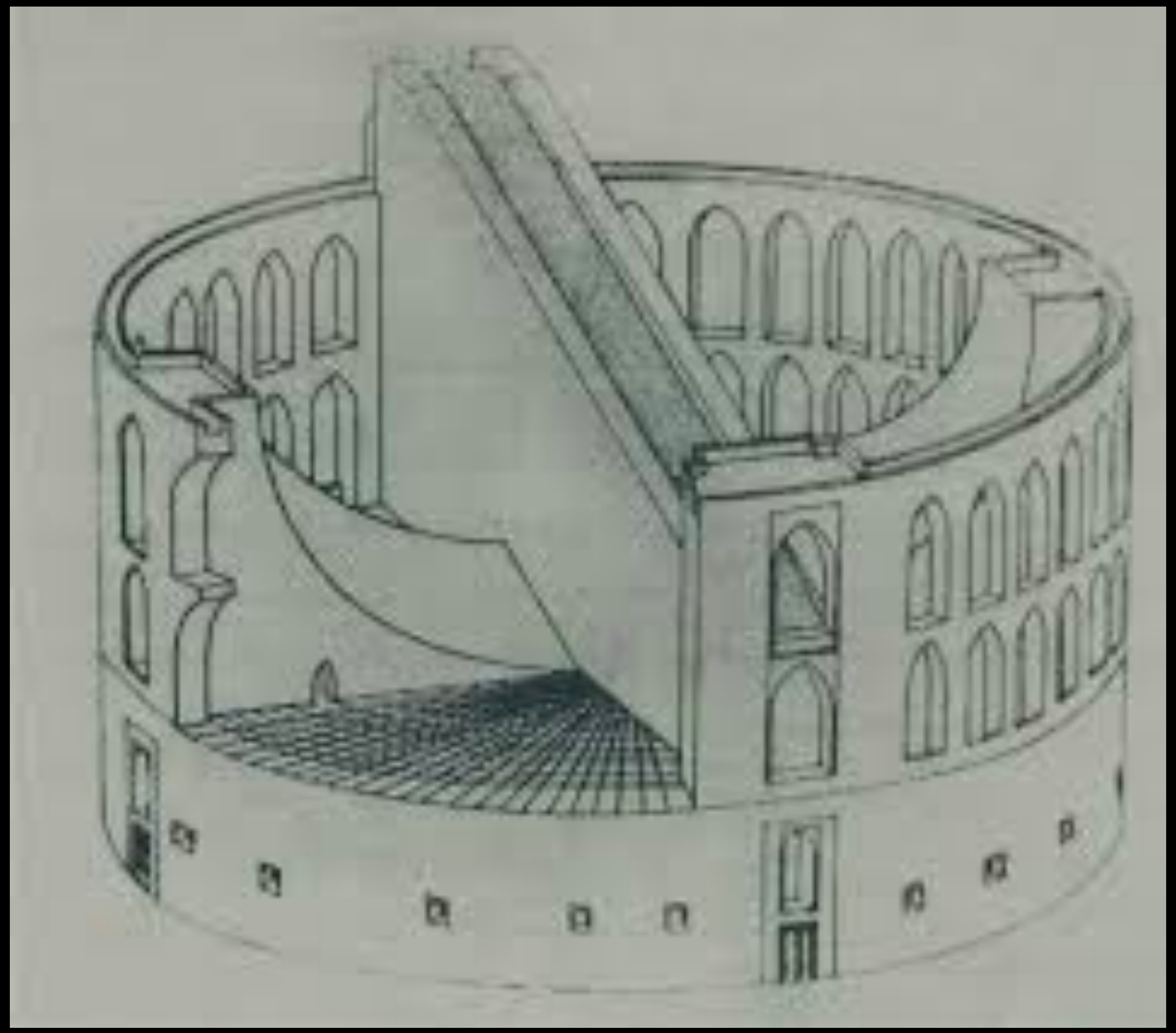
- Intervening years (2nd - 16th Centuries)
  - Al Buruni and Ibn Sina (Avicenna) debate whether there is any evidence that all natural motion is circular (1000 CE)
  - Samarkand observatory builds catalog of 1000 stars and increases accuracy of planetary measurements





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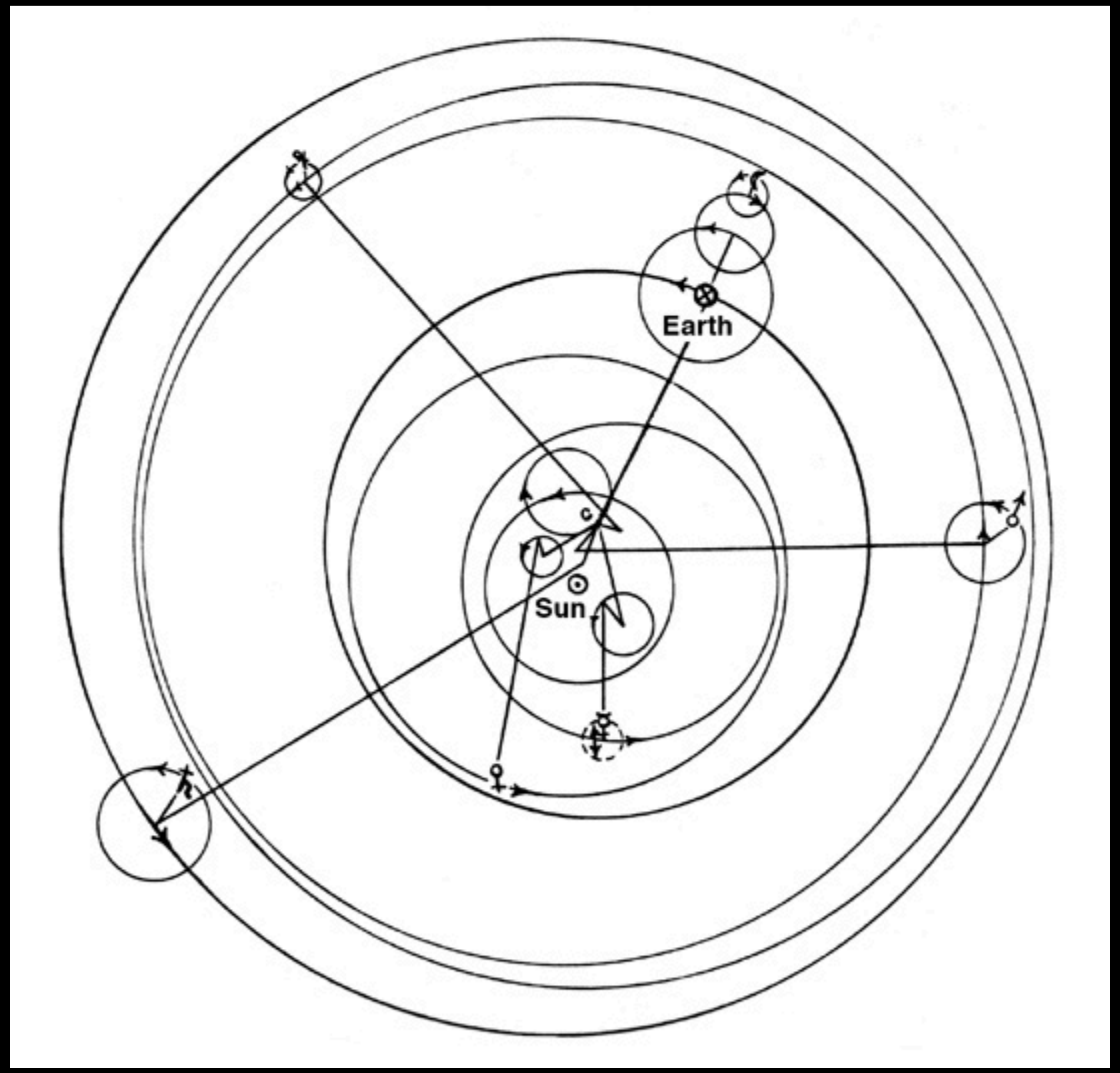
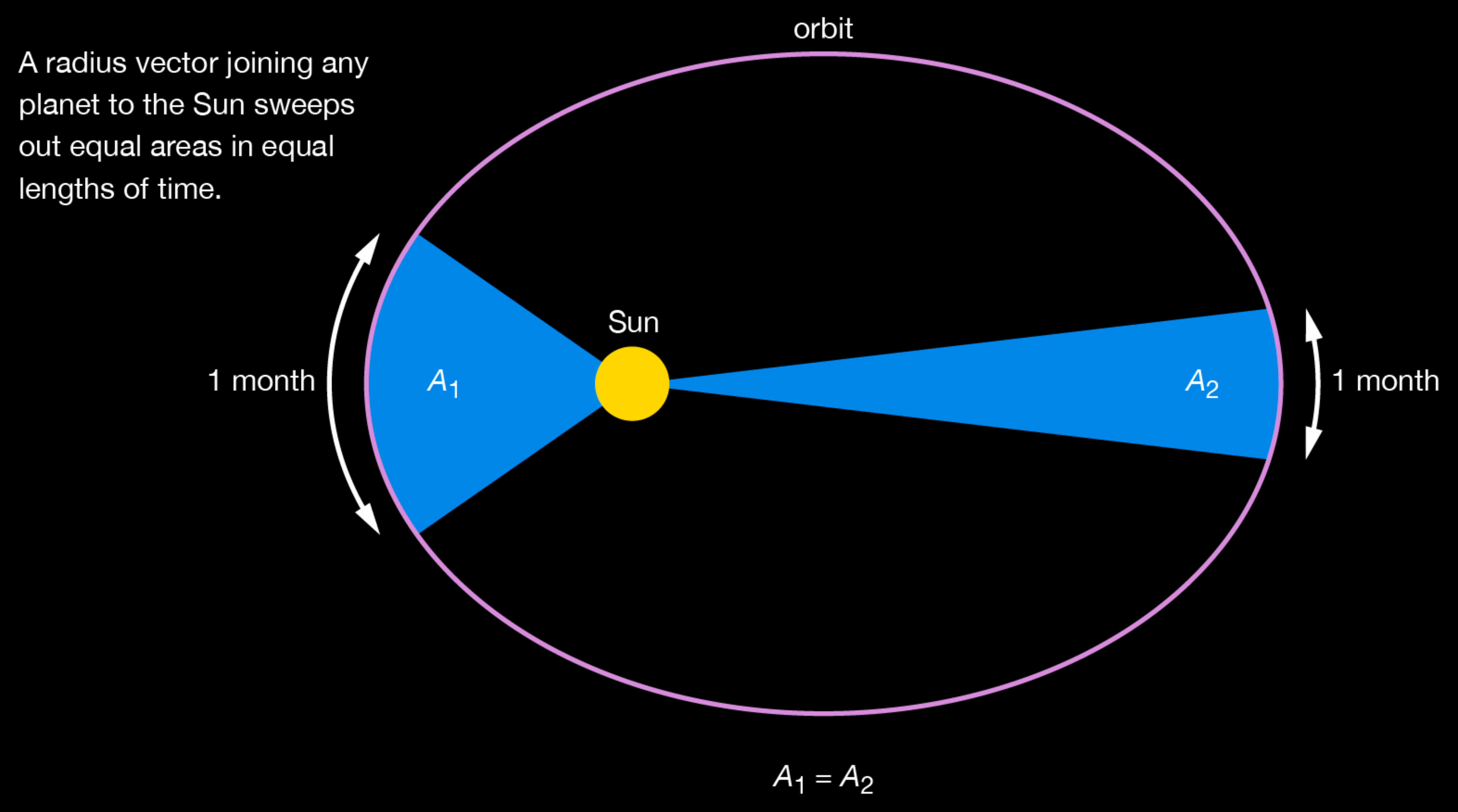
- Heliocentric model comes to prominence (16th-17th century)
  - Copernicus posthumously publishes sun-centered solar system
  - Galileo improves solar system observations and publicly supports heliocentric
  - Tycho Brahe shows that comets move around the sun (1577)



Kepler and Newton

The Birth of Astro-Physics

- Kepler (1609) measures distances in three dimensions between planets and sun, and describes the motion using ellipses.
- Kepler shows that for the known planets, the orbital period and semi-major axis of the orbit are related by a simple formula, and the speed can be related to distance from the sun.
- Relaxing the need for perfectly circular orbits lets us ask what force might generate an elliptical orbit.



$$\frac{T^2}{a^3} = \frac{1year^2}{1AU^3}$$

Kepler and Newton

The Birth of Astro-Physics

- Newton (1687) recognizes that circular (and elliptical) motion result from a central force; if the strength of that force is proportional to the mass of the attractor, that leads to an inverse-square law force

- If you compare the earth-moon and earth-sun systems, you can show that kepler's laws scale with total mass

- First experimental demonstration of distance-dependence of gravity

$$
\begin{aligned}
F/m = a &= \frac{v^2}{r} \\
&= \frac{4\pi^2 r}{T^2} \\
&= \frac{4\pi^2}{r^2 C_{sun}}
\end{aligned}
$$

$$\frac{T^2}{a^3} = \frac{4\pi^2}{G(M_1 + M_2)}$$

Enlightenment Universe

- By the end of the 17th century, we understand that the solar system is gravitationally bound, and begin to study bodies outside the solar system.

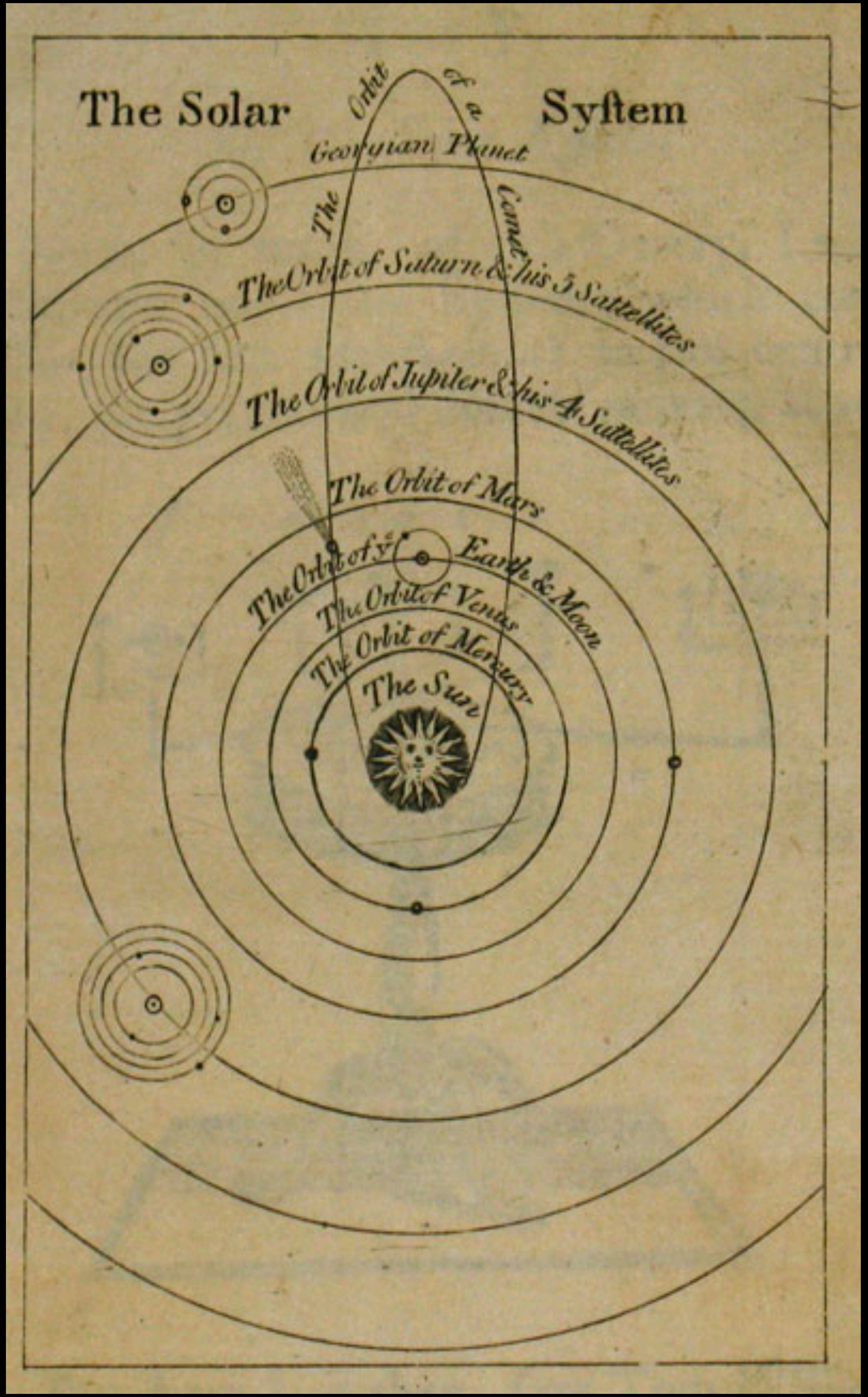
- The major scientific hint involves comets; they seem to come from the ‘stellar sphere’ and circle the sun, then return to beyond the known solar system.

- Comet hunters also start to observe stars and other ‘nebulae’

  - Messier catalogs 110 bright nebulae (1781)

  - Bessel infers that many stars exist in binary systems due to odd motion on the sky (1844)

  - Parsons notes that some of Messier’s objects appear to be rotating clouds (1845)



Mapping Stellar Distributions

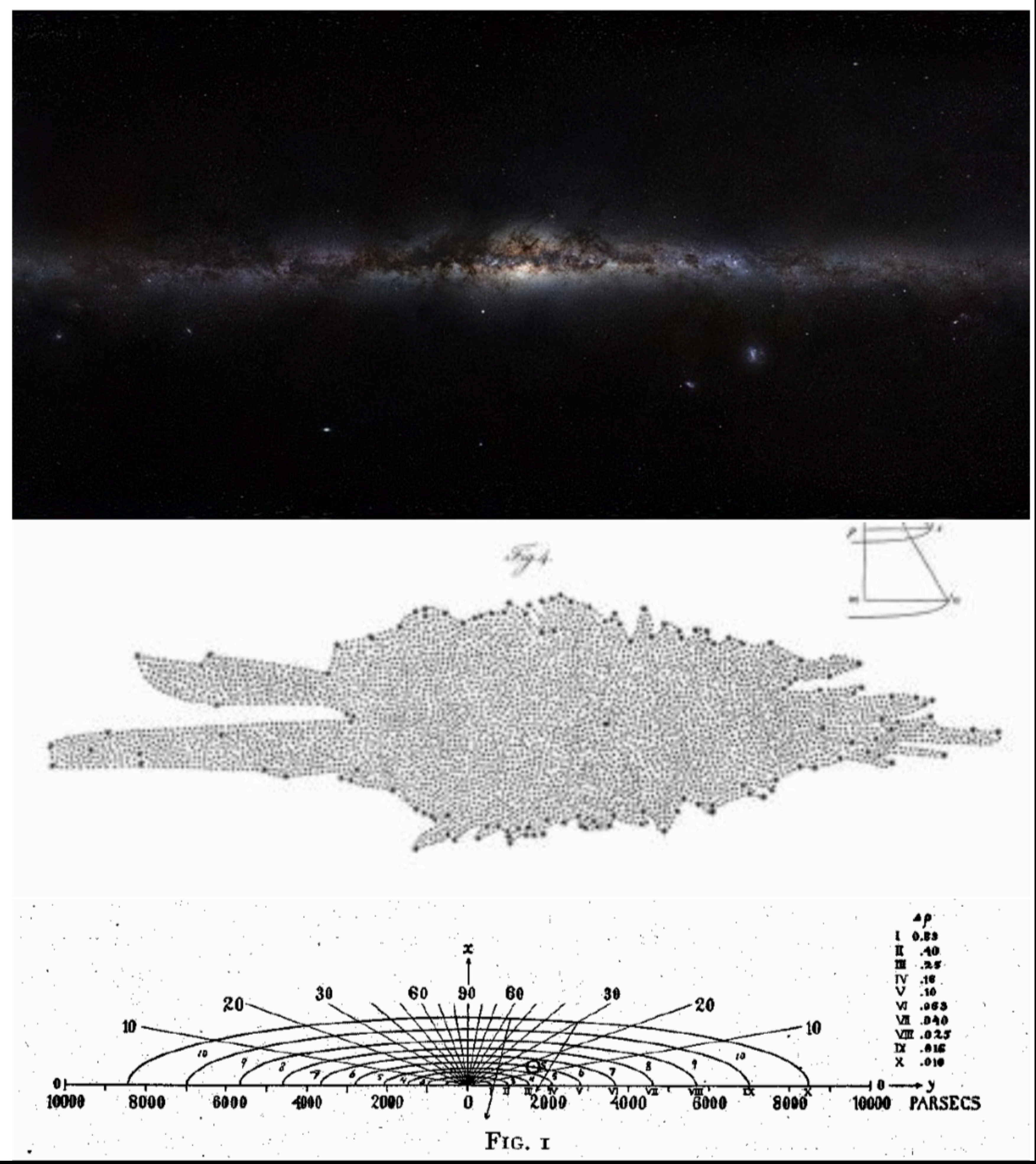
First Extrasolar Maps

- Kant & Wright propose that, if the solar system is gravitationally supported and rotating in a disk, maybe the milky way seen on the sky is an edge-on disk

- Herschel, assuming uniform star density, attempts a map with the sun at the center. He uses his catalog of just shy of 2000 stars

- Kapteyn refines Herschel's method, drawing the first galactic diagram with the sun off-center

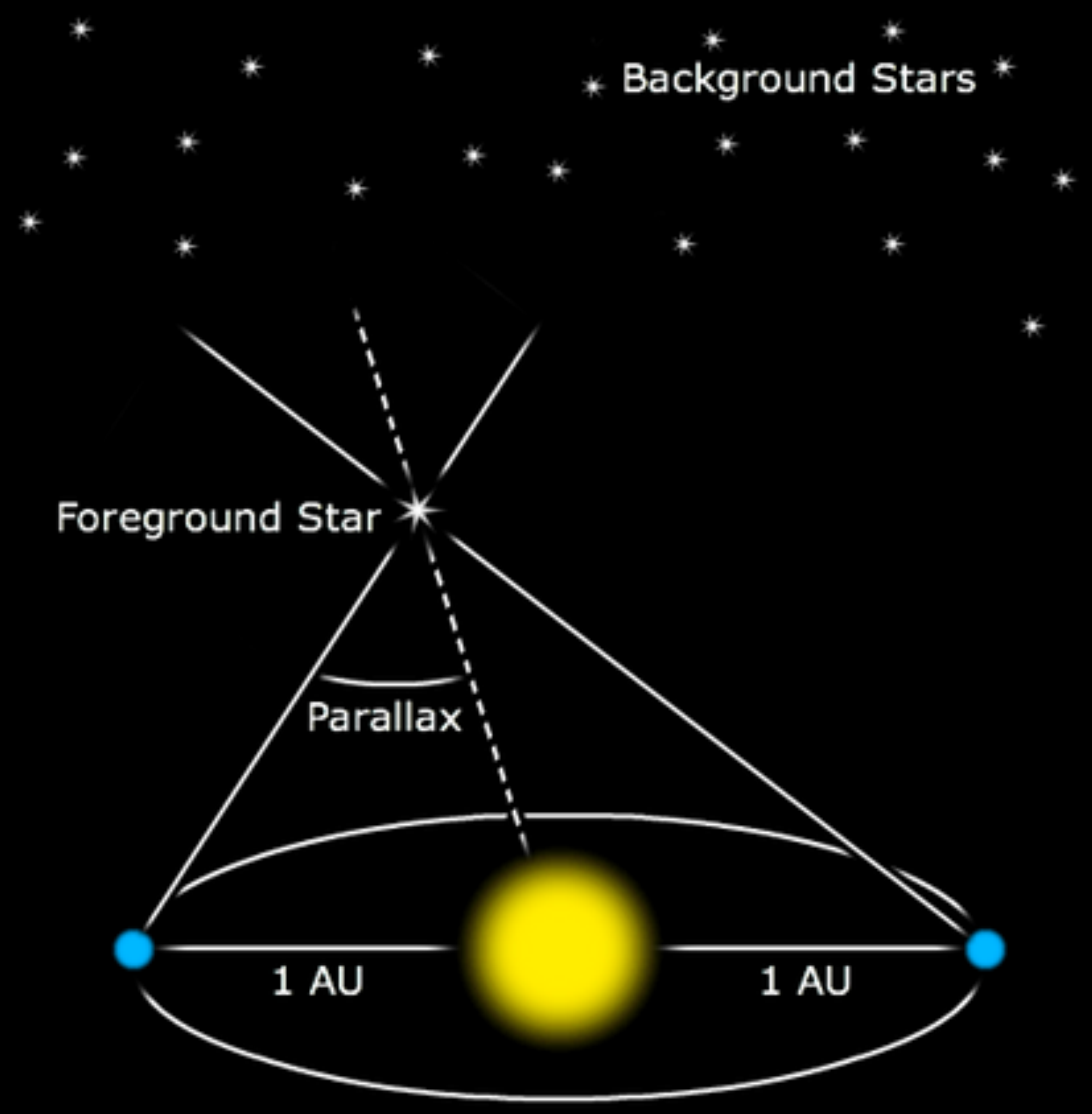
- Astronomers still uncertain as to the origins of the dark clouds across the galaxy



Distance Beyond the Solar System

Stellar Parallax

- We can exploit earth's revolution about the sun to measure the distance to nearby stars!
- Find the angular position of a star compared to the background stellar field on one date
- At a later date, measure again. The difference in angle gives the parallax of the star
- Because the angle is very small, we get a very simple distance relationship!



$$d = \frac{1}{p}$$

http://astro.physics.uiowa.edu/ITU/glossary/stellar-parallax/

Understanding Parallax

Why is the relationship so simple?

$$\frac{1AU}{d} = \tan(p)$$

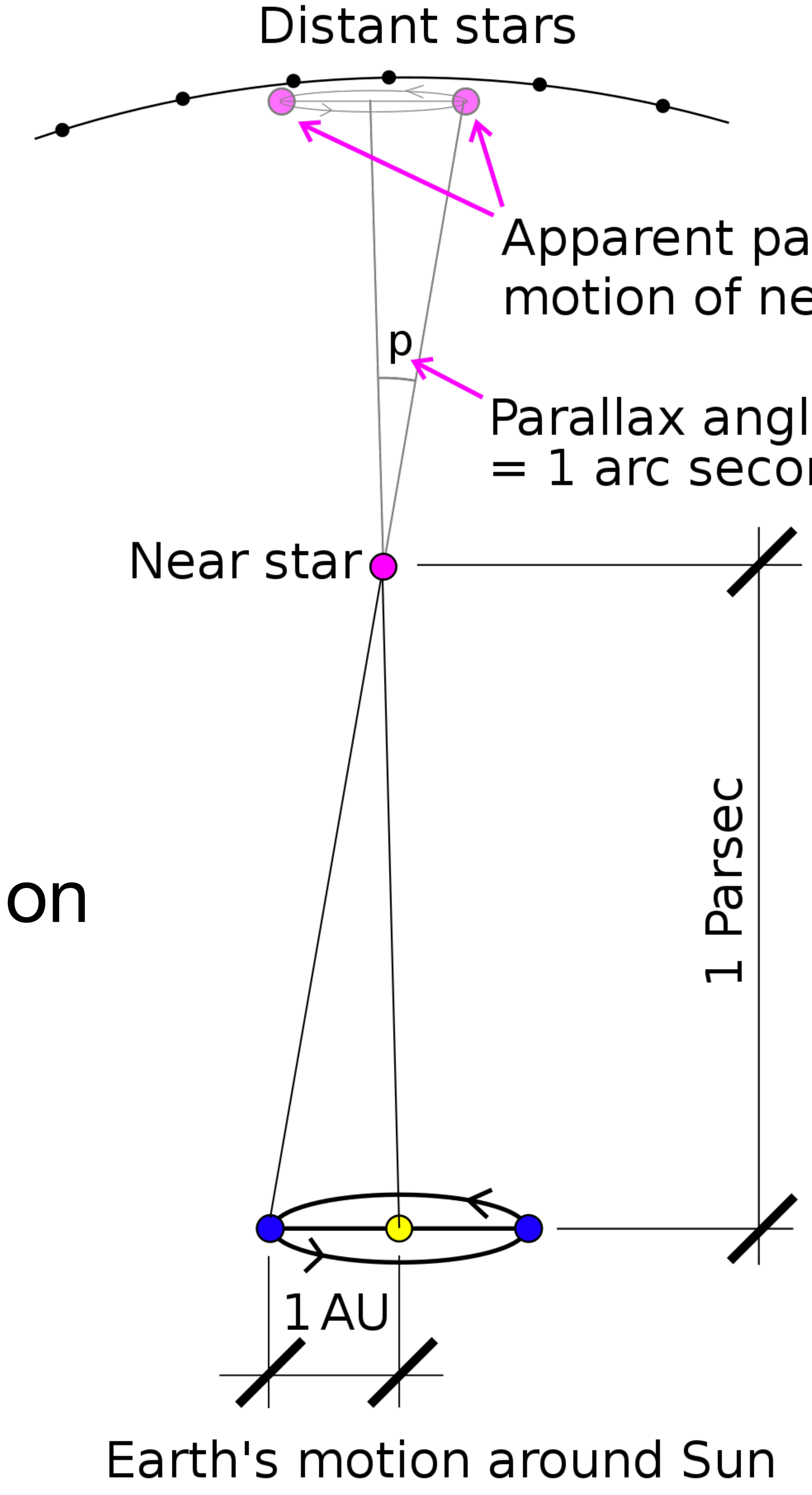
$$\approx p + \frac{1}{3}p^3 + O(p^5)$$

$$\rightarrow d = \frac{1AU}{p}$$

If angle is less than ~10 degrees,
we can make a ‘small angle’ approximation
and get this simple relationship

$$1AU * 1.58 * 10^{-5}\,\frac{\mathrm{ly}}{\mathrm{AU}} * 206265\,\frac{\mathrm{arcsec}}{\mathrm{rad}}$$

$$= 3.25\,\frac{\mathrm{ly}}{\mathrm{arcsec}} = 1\,\frac{\mathrm{pc}}{\mathrm{arcsec}}$$

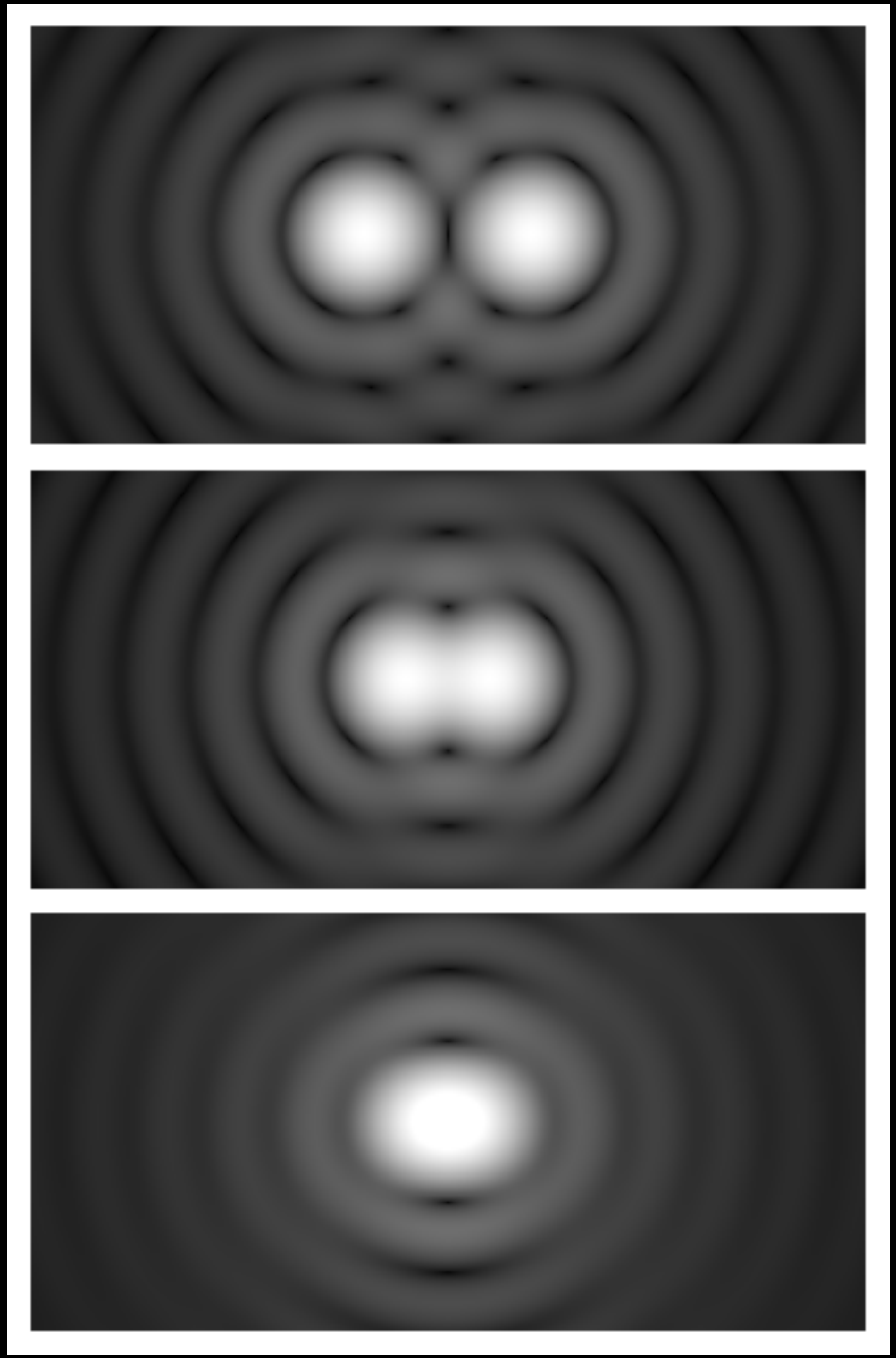


How Far Does This Work?

- Parallax limited by a few different factors
  - Telescope angular resolution

$$\theta = 1.220\frac{\lambda}{D}$$

  - Atmospheric distortion
  - Collection area
  - Sensor sensitivity



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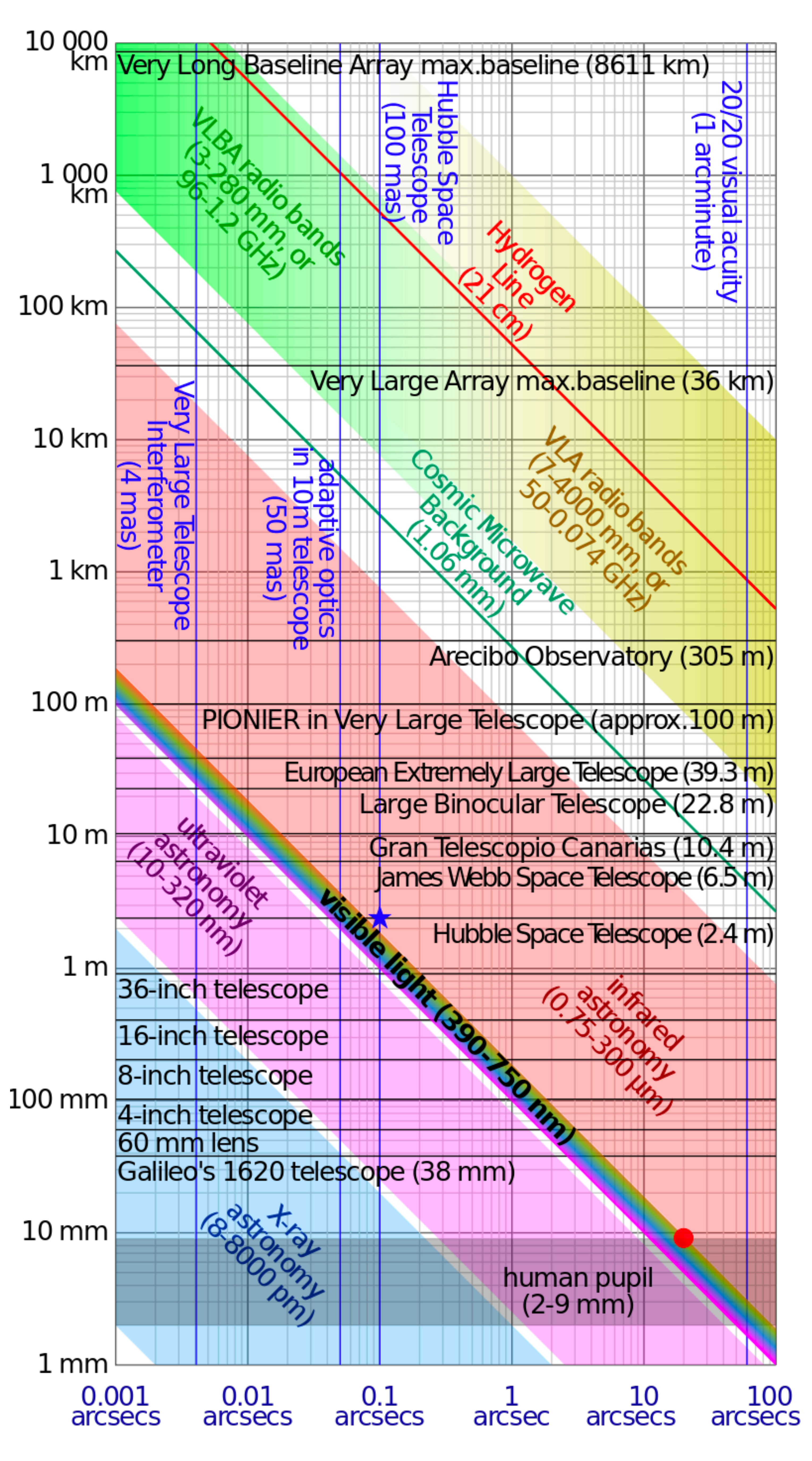
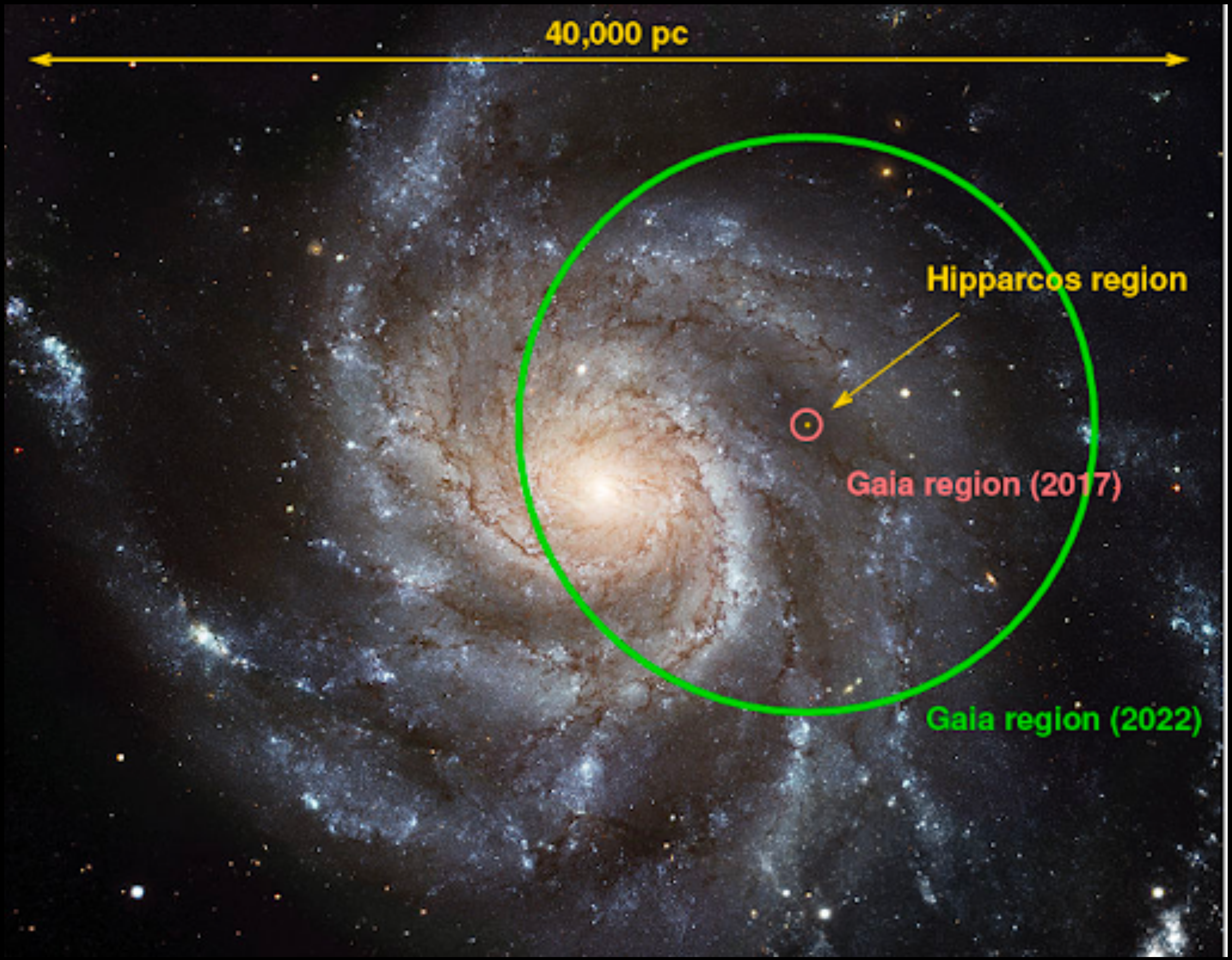
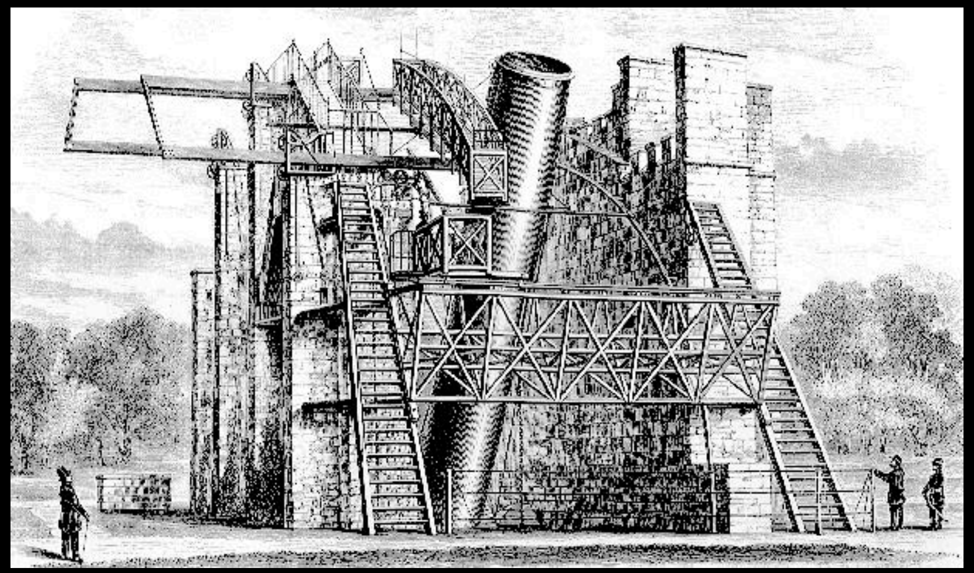
  - Collection area
  - Sensor sensitivity
- If you're observing in the 19th century, you're using ~10cm telescopes with photographic plates; you can't measure distance beyond the stellar neighborhood (about 100 ly)

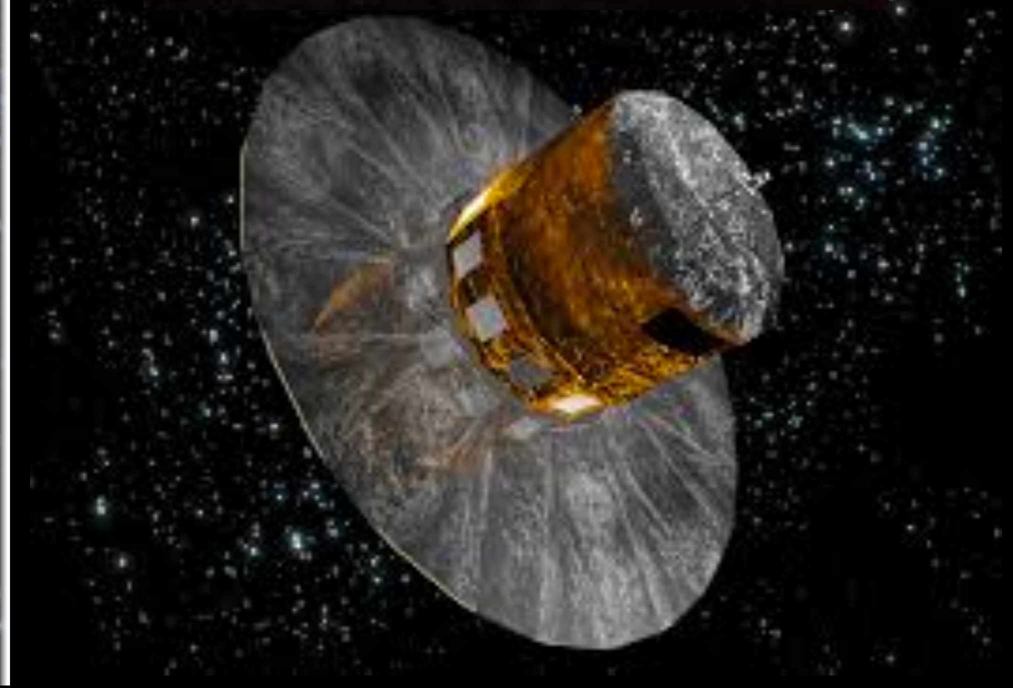


Parallax Measurements to Date

Space-Based Telescopes Win







Stellar Physics

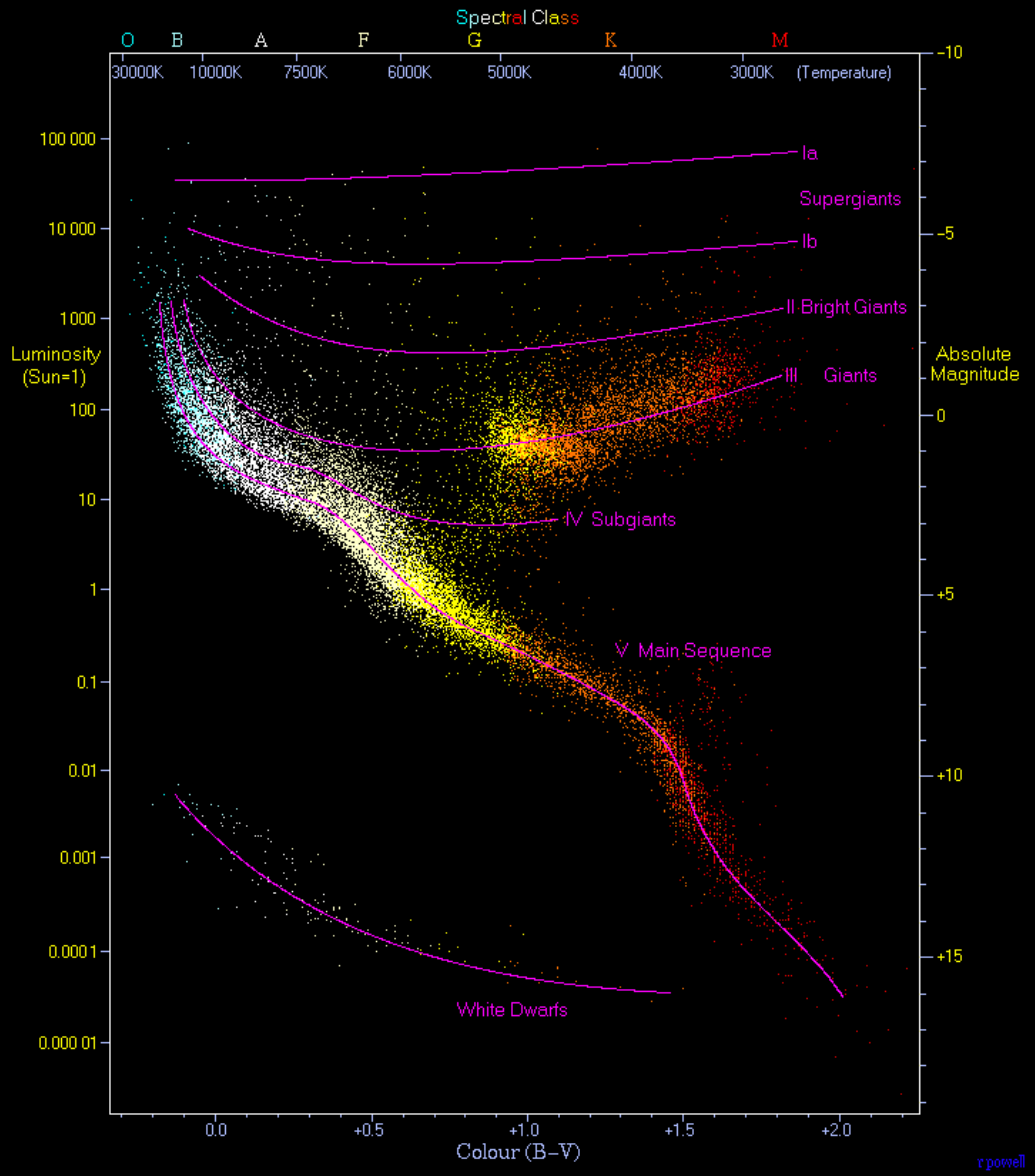
A Pause in the Historical Narrative

Stellar Properties

The Main Sequence

- Once we have distances to stars, I can make a plot of absolute brightness of the star versus temperature
  - Brightness comes from distance correction
  - Color is determined by measuring intensity as a function of wavelength, and correlates with surface temperature

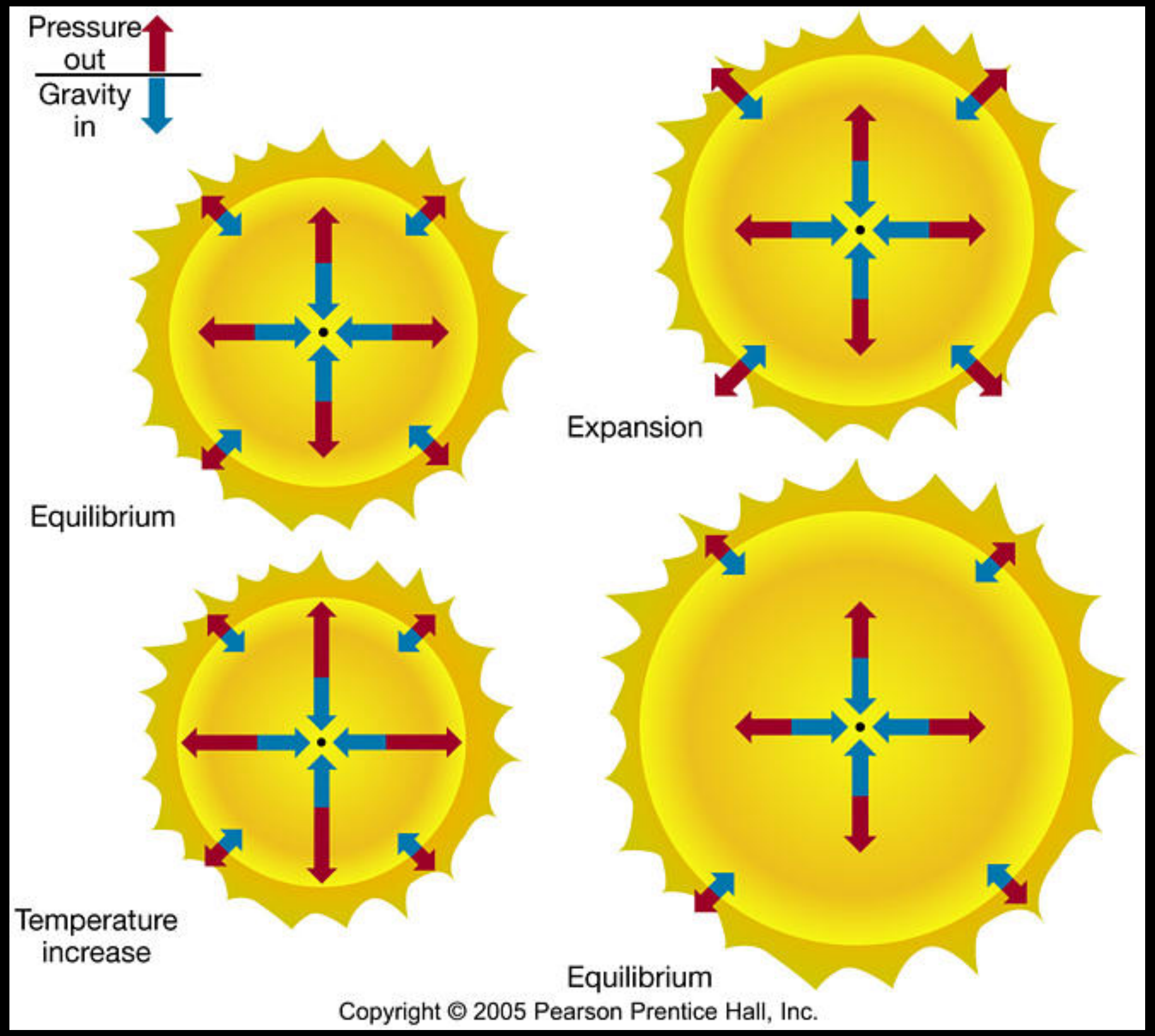
- There's an obvious grouping, and a distinct feature: the main sequence
  - The majority of the stars lie along this band

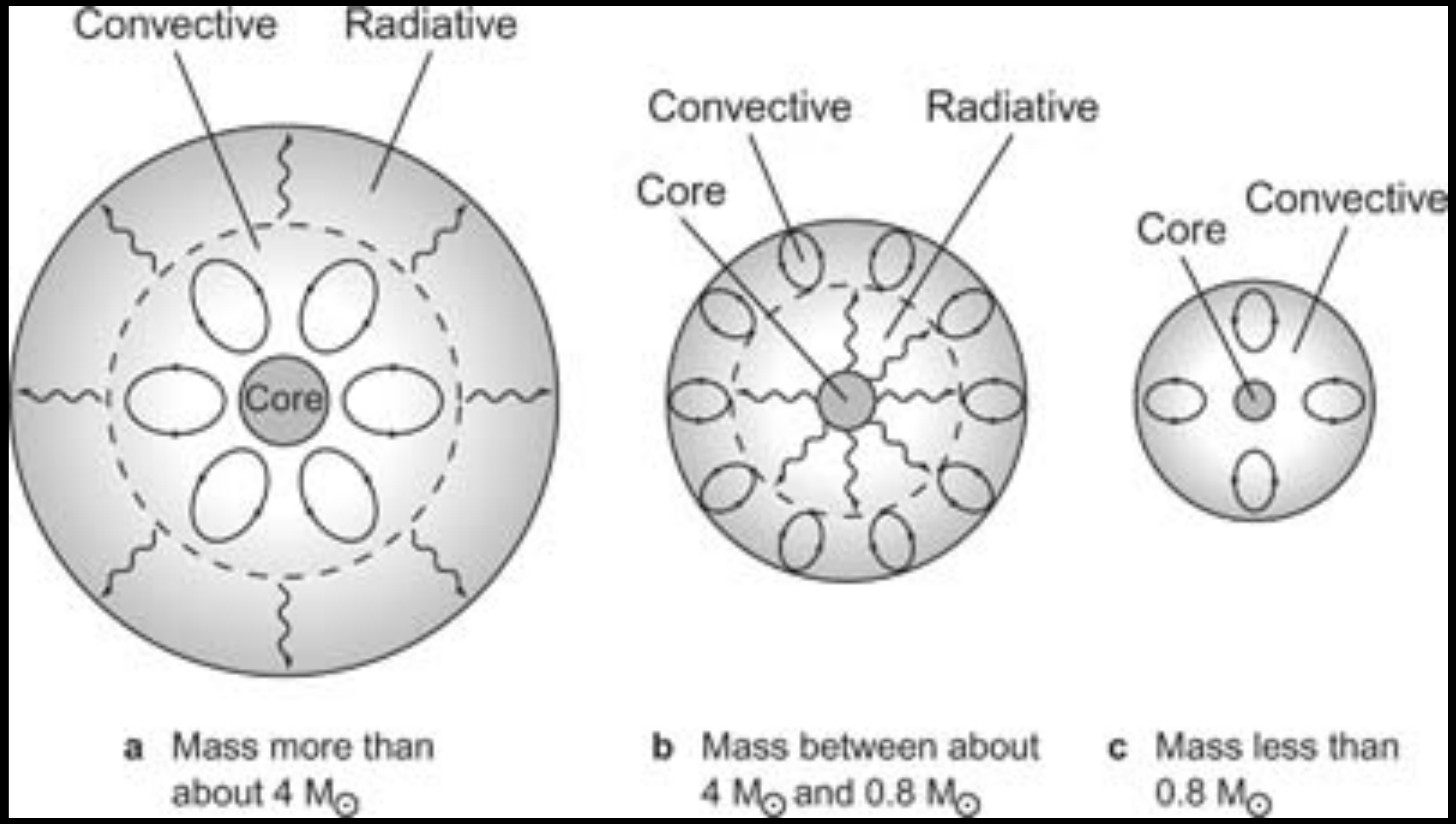


Physics of Stars

What is a Star, Really?

- Stars are just self-sustaining explosions, regulated by pressure and temperature
  - The core is heated by fusion, which produces radiative pressure
  - The radiation also heats the external layers of the star, producing outward gas pressure
  - Large stars transfer heat by convection; they boil!
  - Gravity pushes back inwards on the star
- Stable stars (stars on the main sequence) are heavy enough to sustain fusion, and light enough that the fusion isn't a run-away process





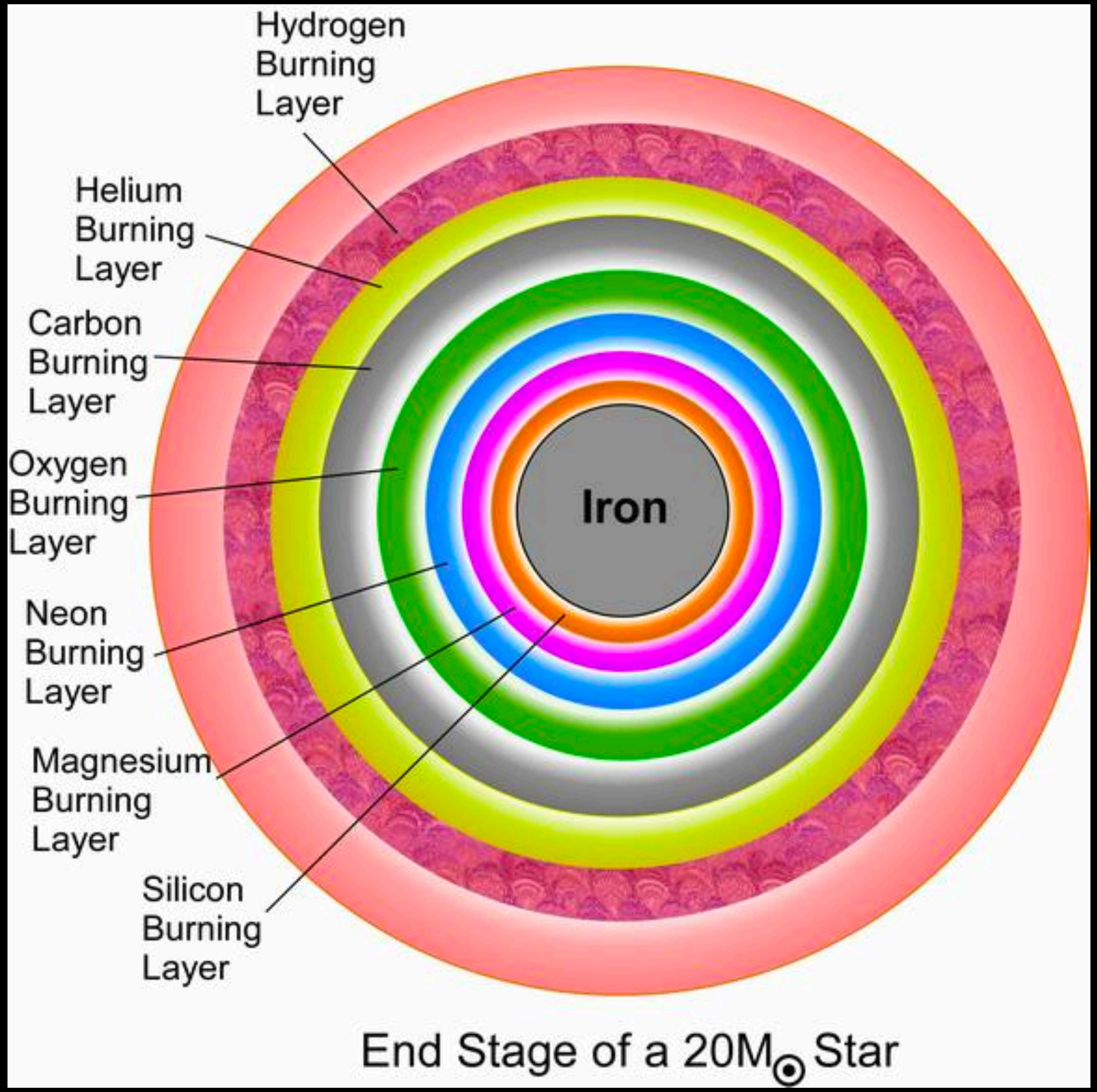
Star Formation

Fusion Processes

- Hydrogen Burning
  - PP Chain - turning hydrogen into Deuterium and Helium
    - 4H -> 1 He
    - I, II, III
  - CNO Cycle - once enough carbon is present, at high temperatures, carbon is used as a catalyst to generate nitrogen, oxygen, and helium

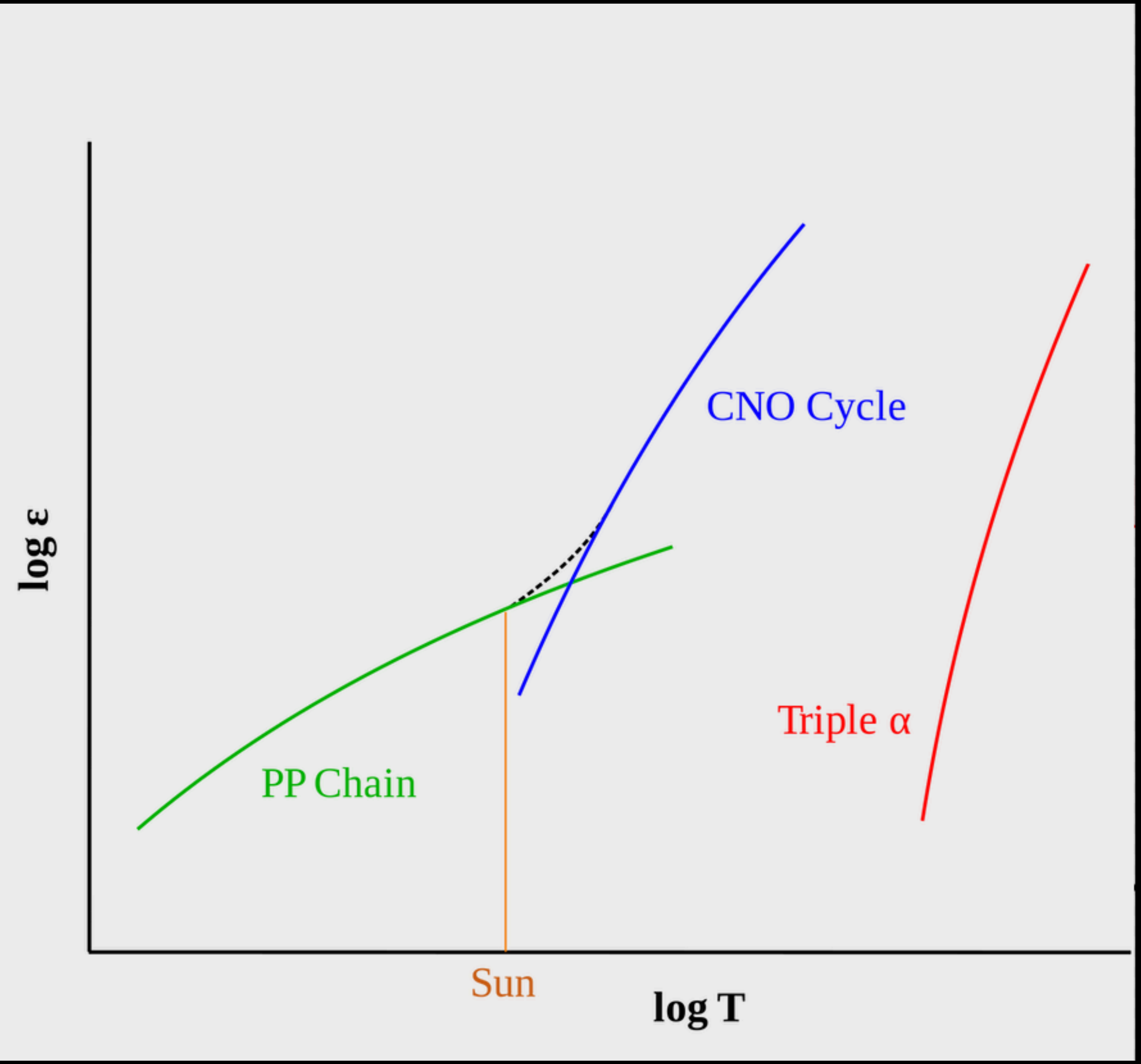
- Helium Burning
  - Triple Alpha Process (3He -> C12)
  - Alpha Ladder (He + X)

- Heavy Element Fusion



Star Stability

- Rate of fusion goes as the core temperature of the star
- Larger stars require more outward pressure to balance gravity, and their cores heat up to get higher fusion rates
  - Higher fusion rates burn fuel much faster
- Rates of fusion are exponentially related to core temperature, so high mass stars are incredibly unstable!
- If a gas cloud collapses but can't heat its core enough, it won't become a main sequence star
  - These are called brown dwarves, but if they orbit a star, they're often called 'super jupiters'
  - Jupiter is actually more massive than some of the smallest brown dwarf stars



HR diagram gives us a Mass-Luminosity relation:

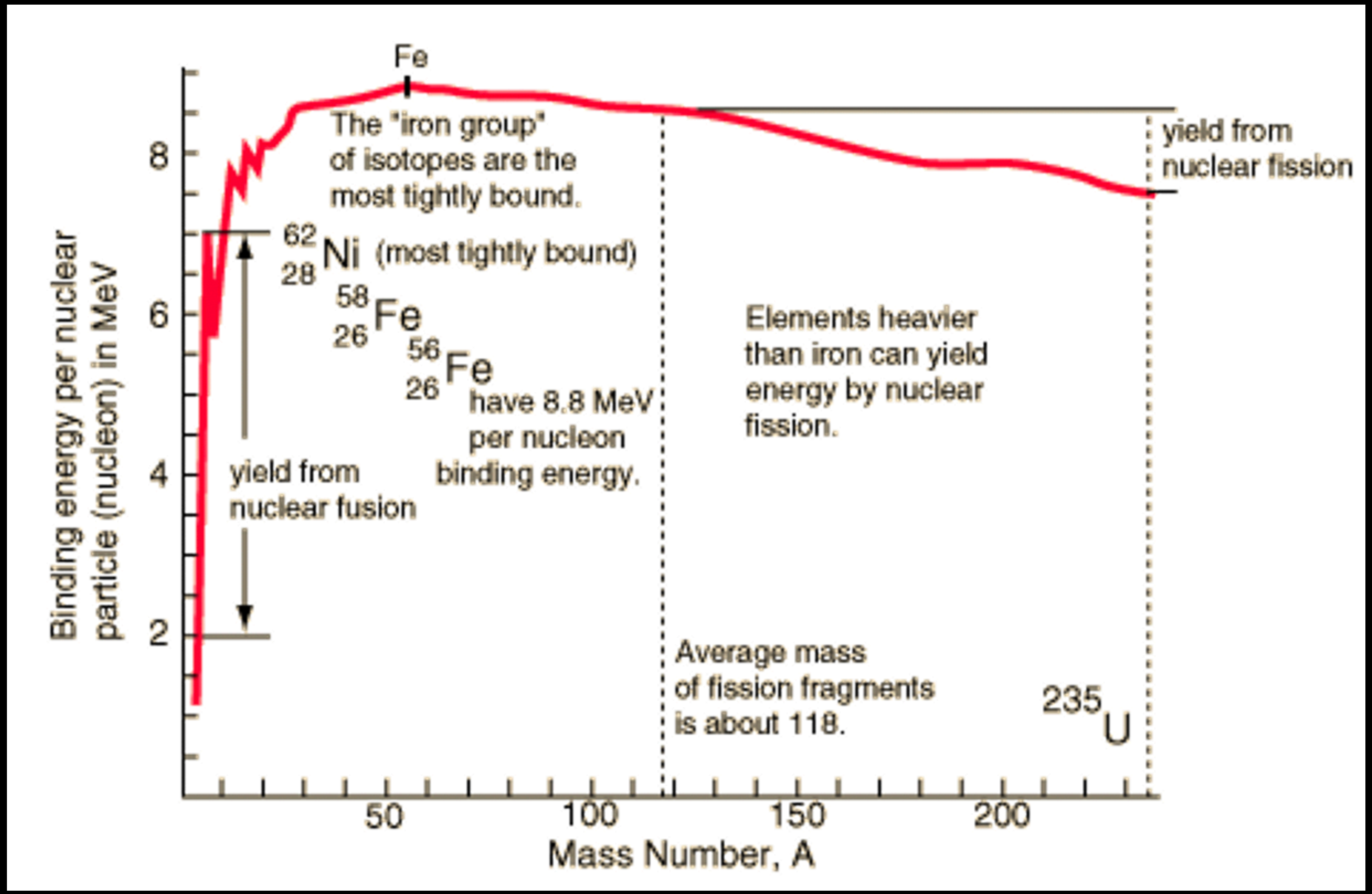
$$L \propto M^{\beta}, \beta \in [3,5]$$

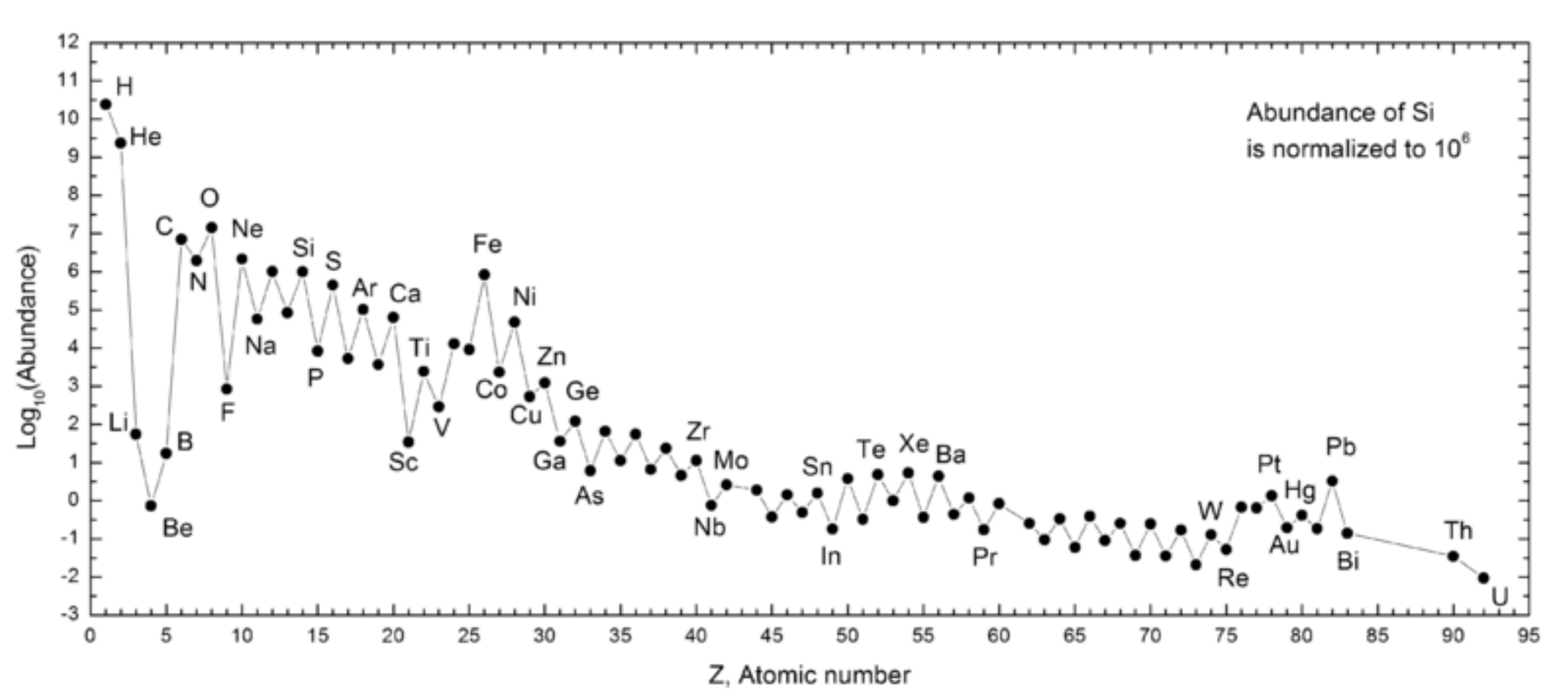
Stars support themselves through radiation, which is sustained through fusion. Lifetime related to amount of fuel:

$$T_{MS} \propto \frac{M_H}{L} \propto \frac{M}{L} = M^{1-\beta}$$

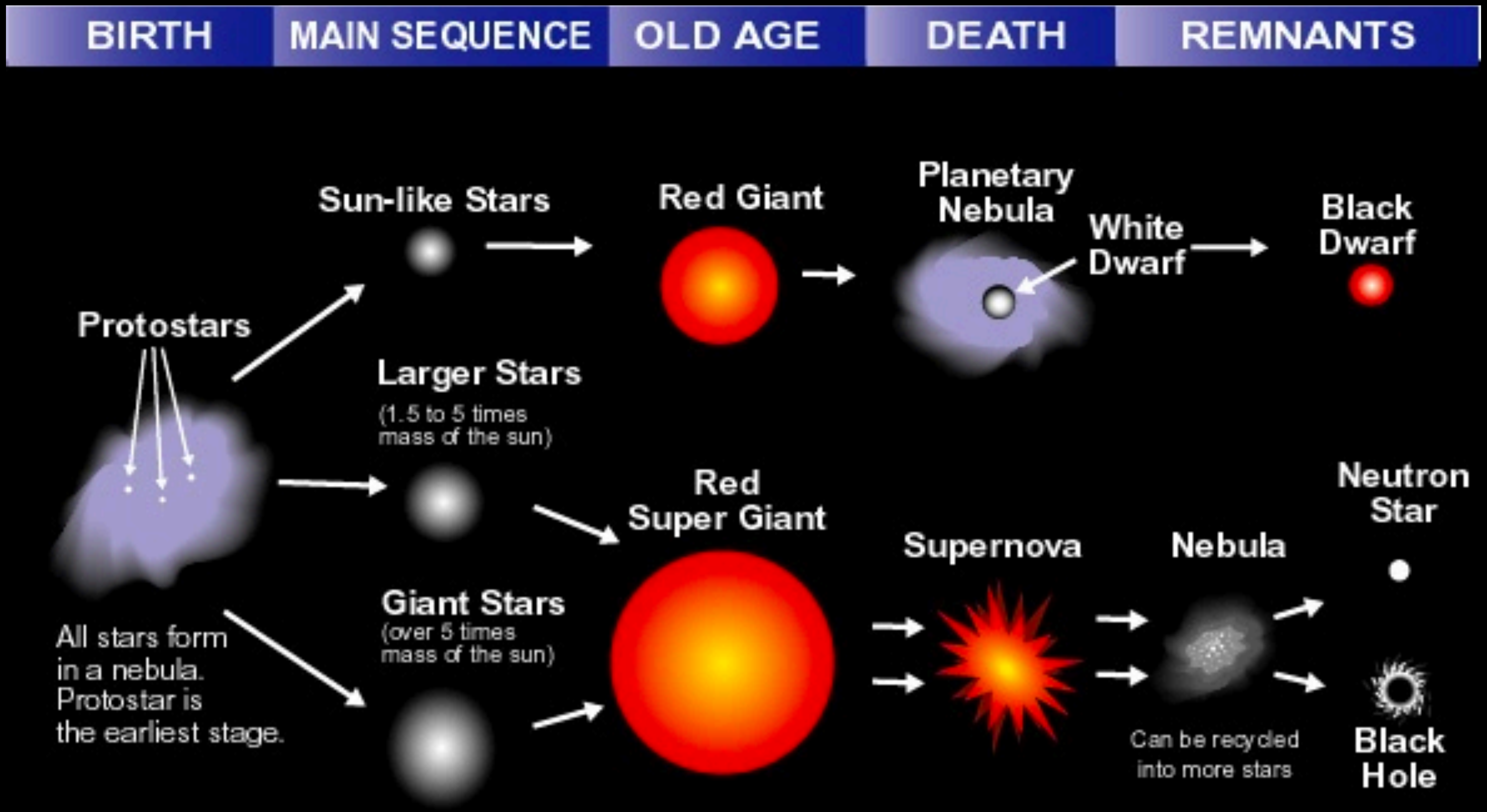
Star Death

- Stars that fuse iron will eventually go supernova
- Fusing of iron absorbs energy; rather than heating the star by fusion, fusing iron or heavier elements cools the core of the star
- Heavier elements largely made in supernovae
- We can see the effects of fusion cycles and supernova nucleosynthesis in atomic abundance data; multiples of 4 much more common due to alpha ladder processes.



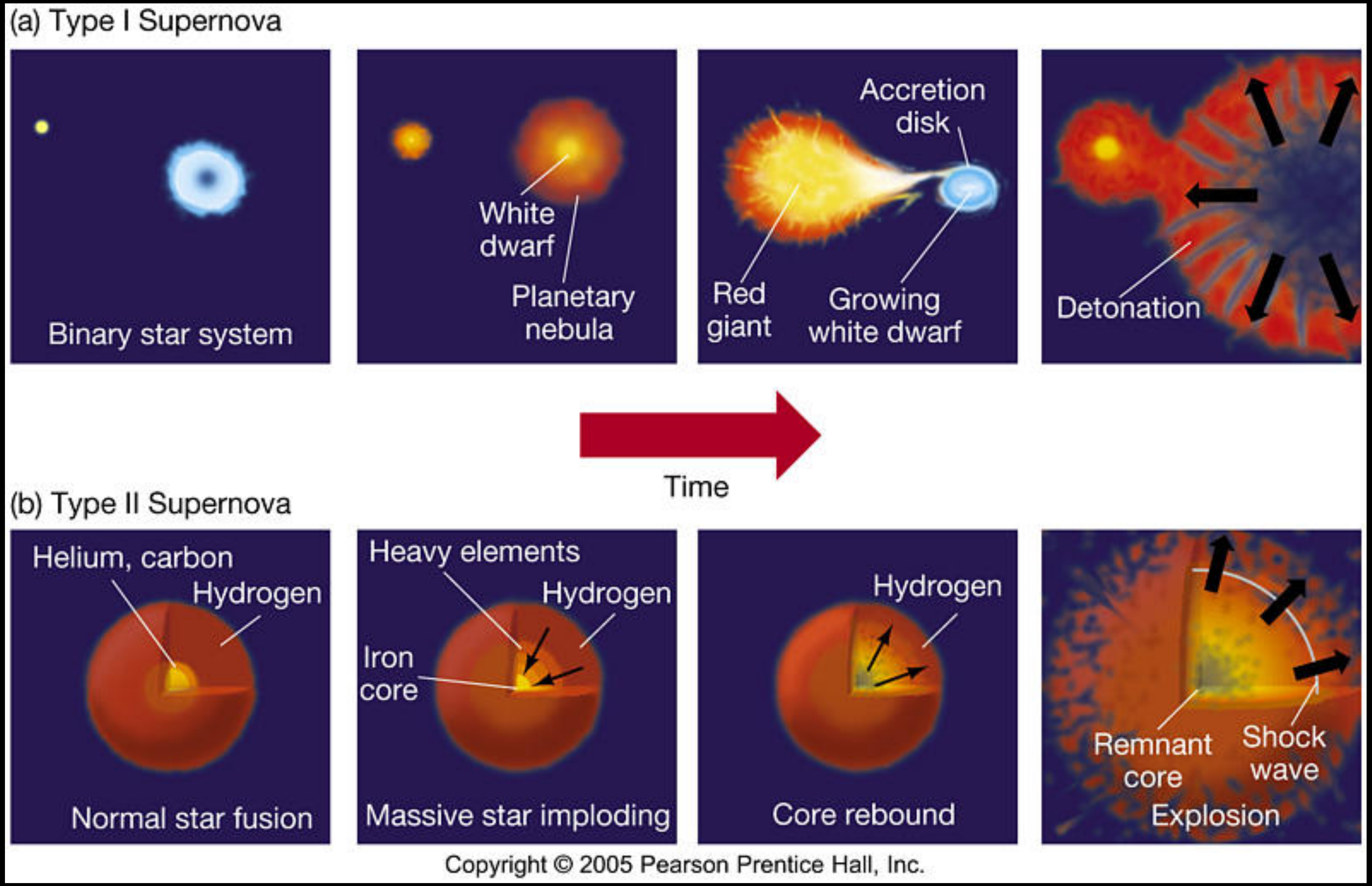


Stellar Evolution



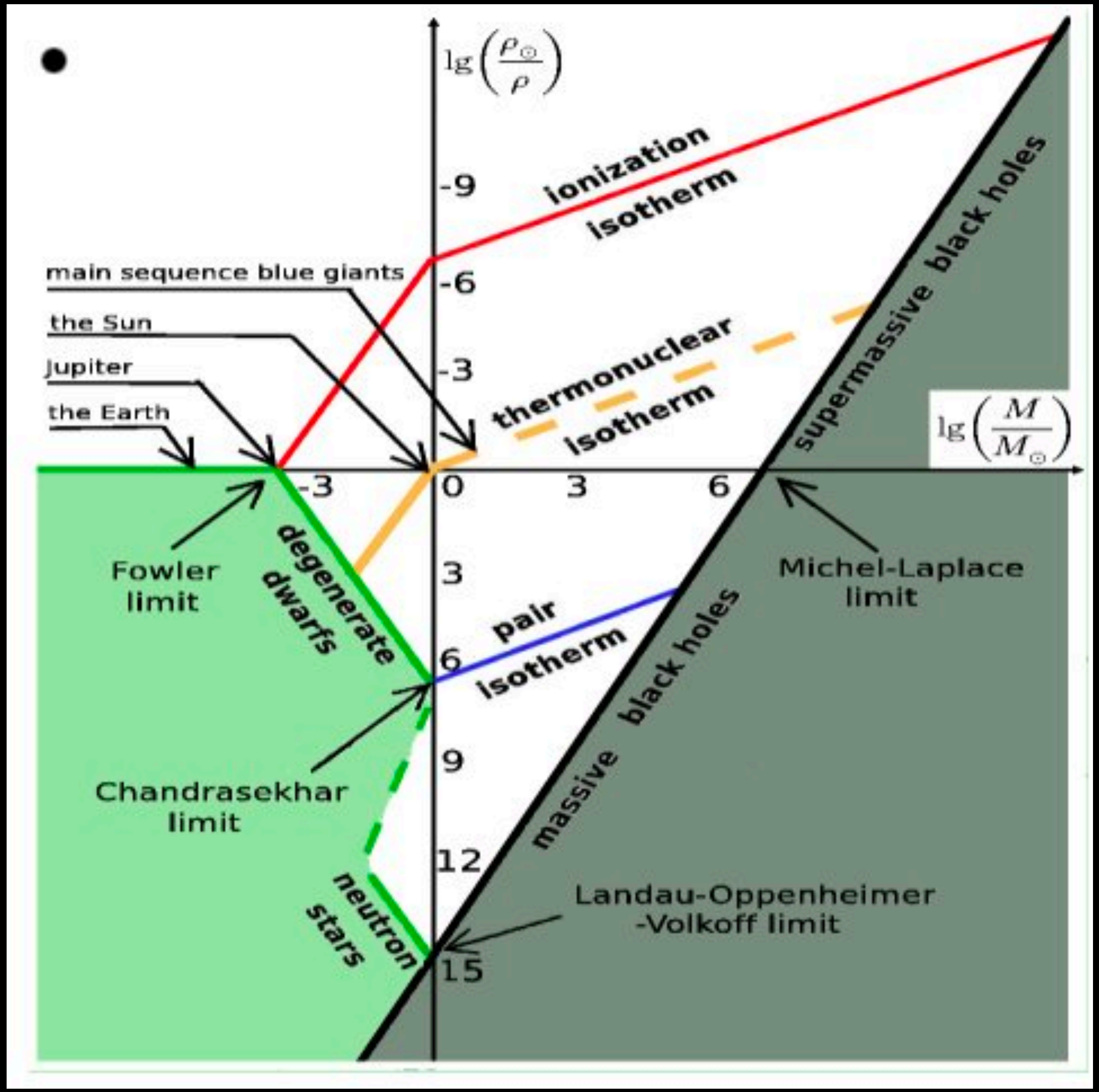
Supernovae

- Type 1a: White dwarf accretes enough gas from a companion to exceed its maximum mass
- Type II: star implodes, generating a massive fusion shockwave that destroys the star (leaving a remnant behind)



Stellar End Stages

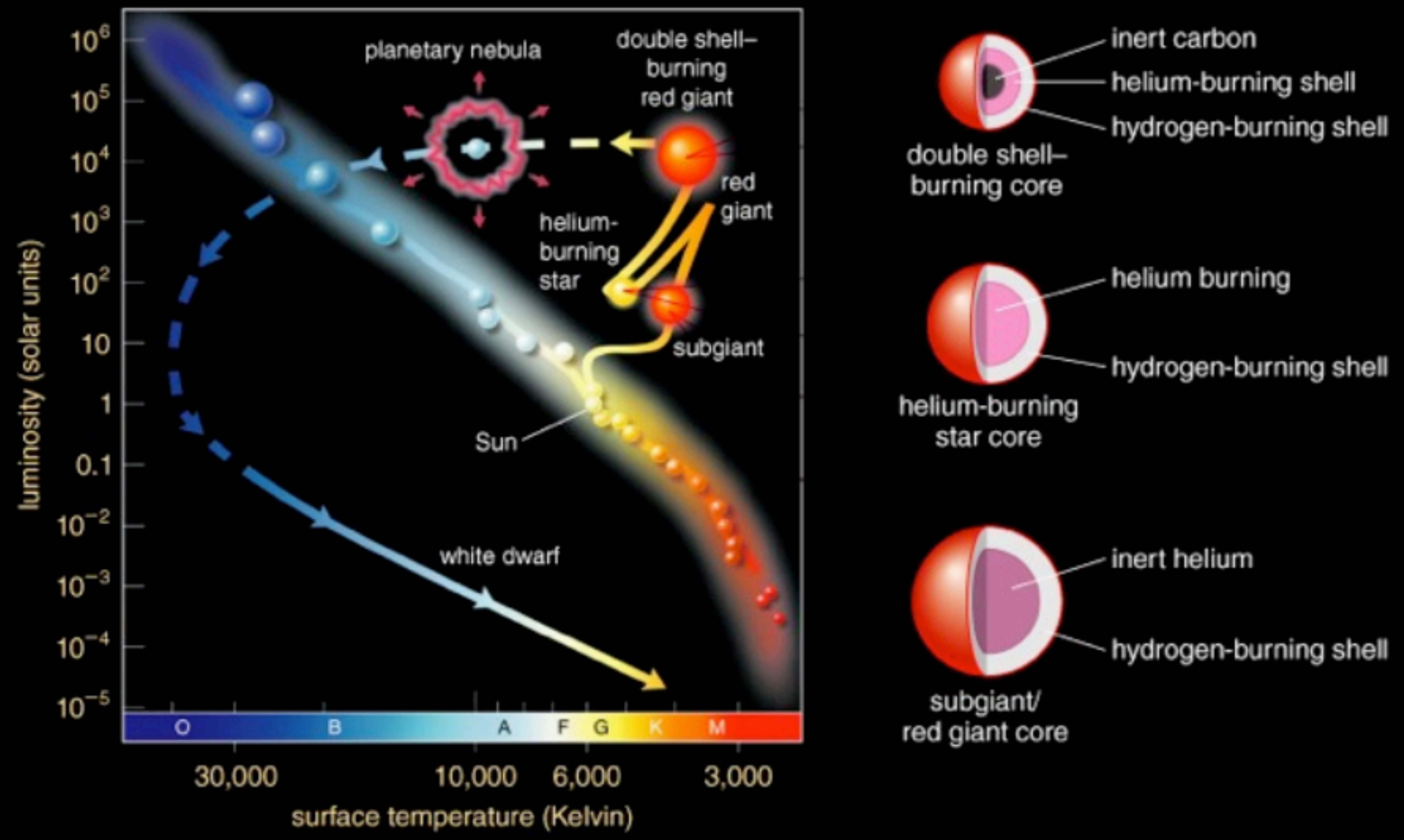
- Mass determines how a star will end its life
- White dwarf stars are supported by electron repulsion (electron-degeneracy pressure)
  - Chandrasekhar mass is the maximum mass that this pressure can support
- Neutron stars occur when electrons and protons combine above the Chandrasekhar mass, supported by neutron degeneracy pressure
  - Landau-Oppenheimer limit is the larger mass supportable by neutron pressure
- Black holes have no minimum or maximum mass; if mass is compressed within the event horizon, a black hole will result.



Schwarzschild Radius

$$r_s = \frac{2GM}{c^2}$$

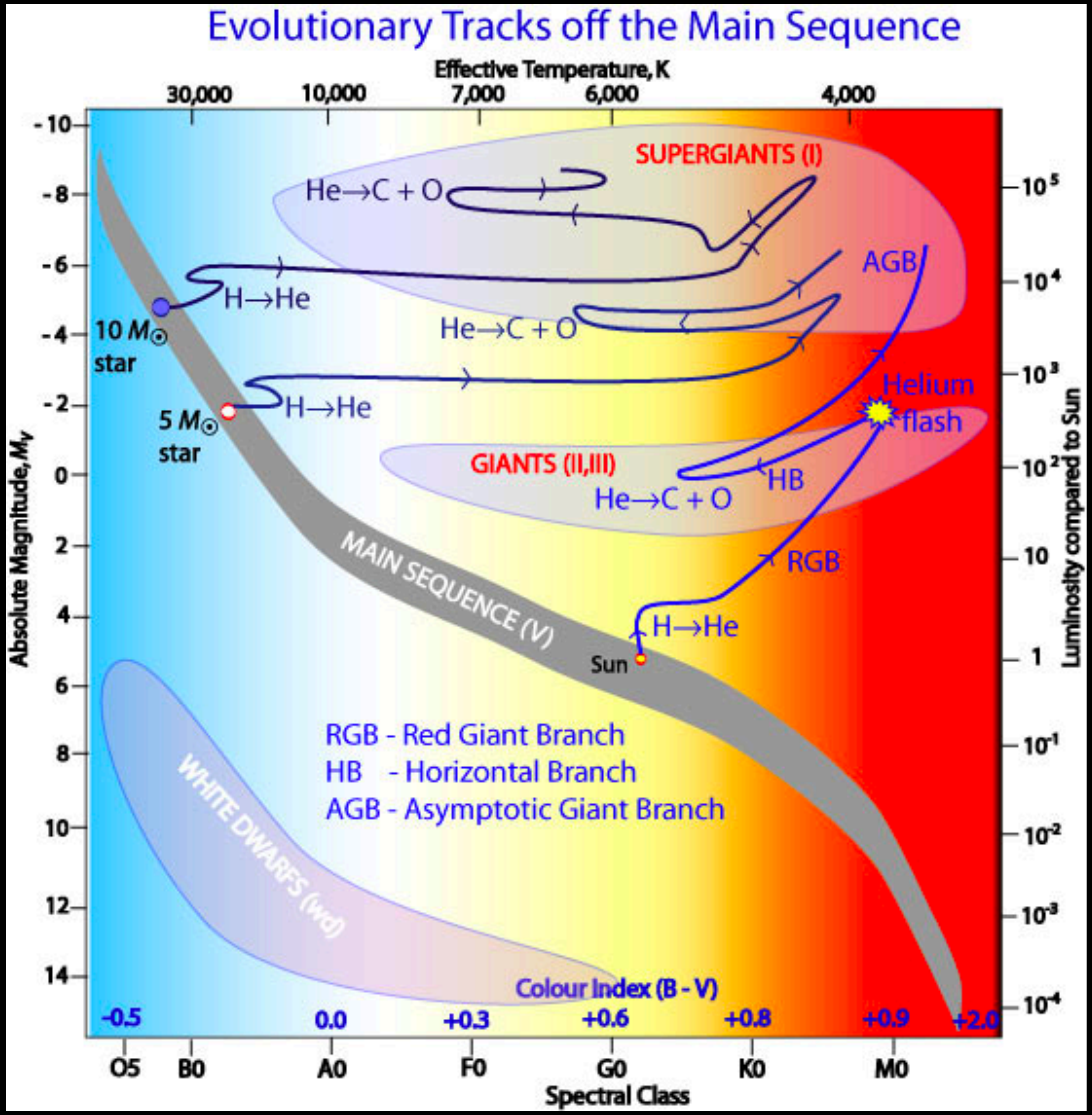
Main Sequence Evolution



Main Sequence Evolution

Higher-Mass Stars

- More fusion phases, shorter lifetime, more active life cycle.
- End stage not on HR diagram because neither neutron stars nor black holes are luminous
- As you go further up the main sequence, it becomes less stable; lifetime of stars is almost too short for them to settle to the main sequence



Cepheids Variable Stars

Instability on the HR Diagram

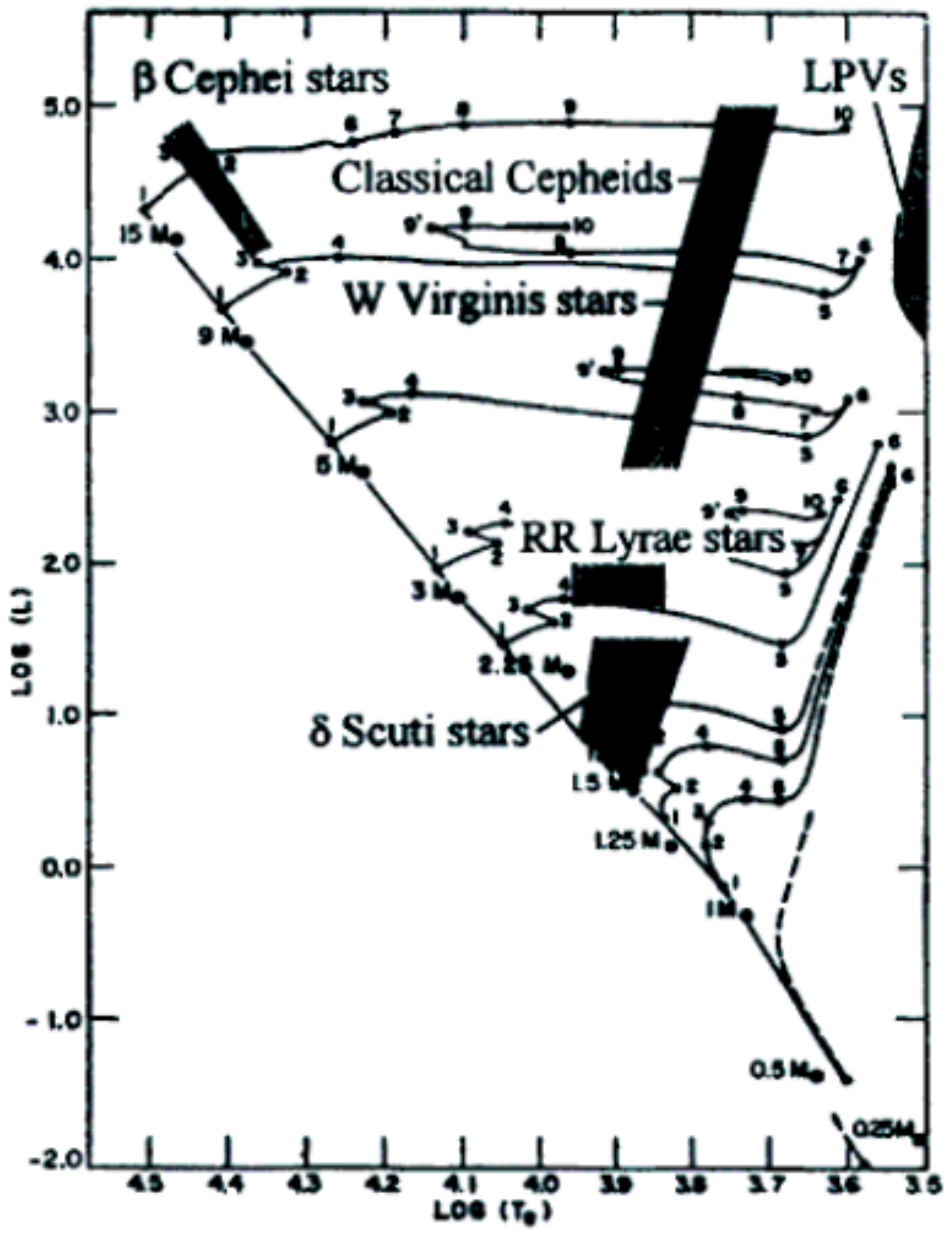
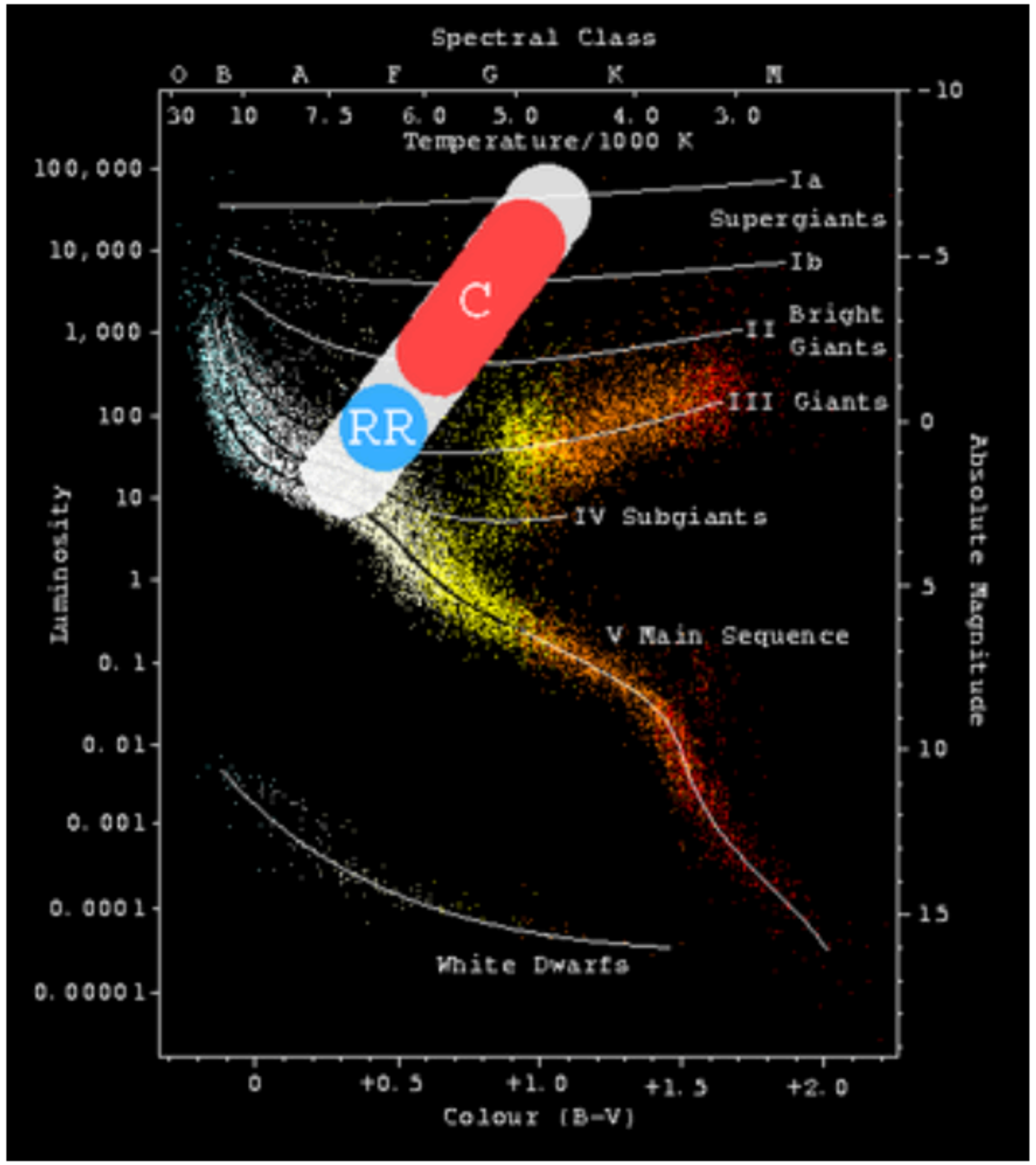
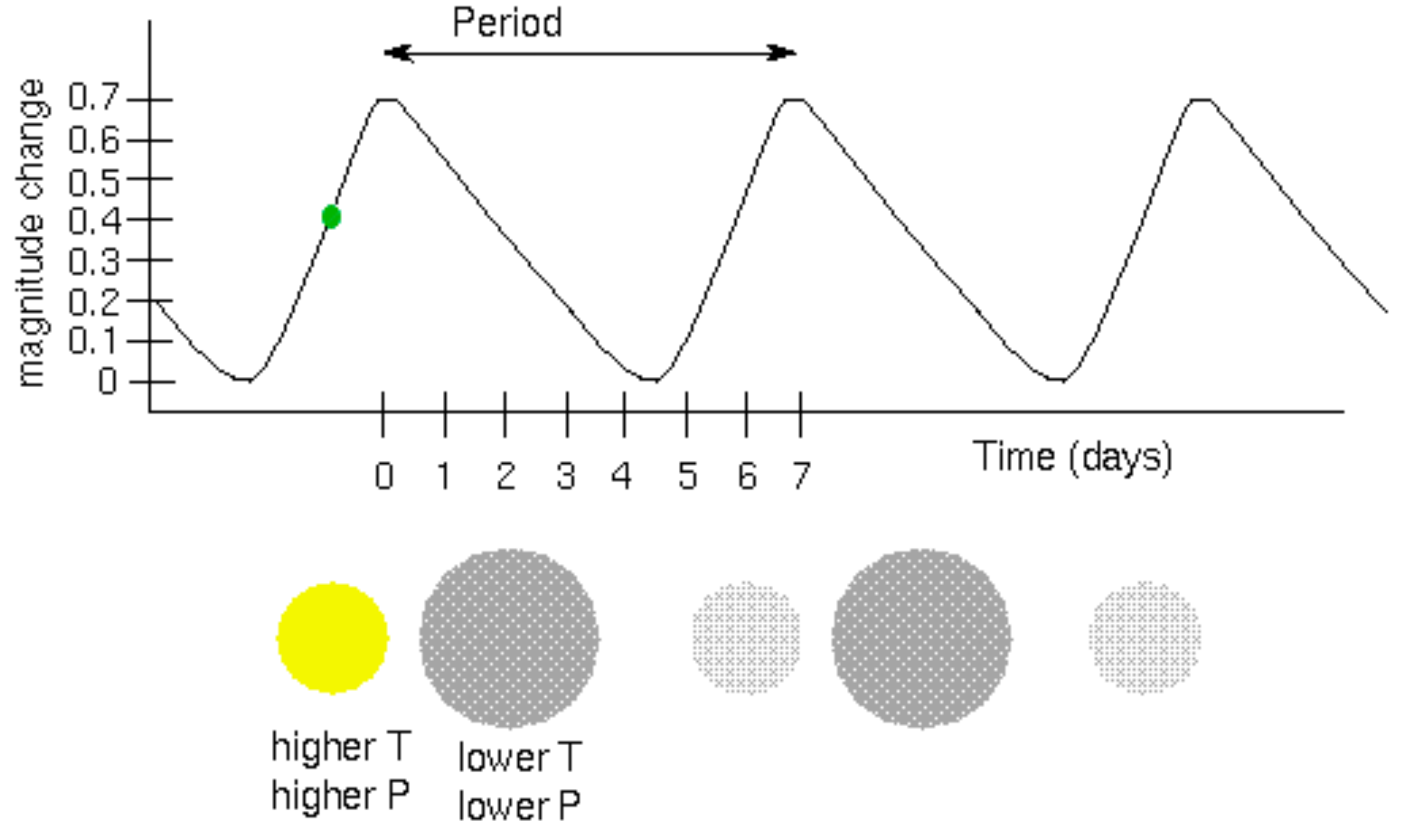


Figure 14.6 Pulsating stars on the H–R diagram. The evolutionary tracks are incomplete, and those of the lower-mass stars extend into the LPV (long-period variable) region. (The evolutionary tracks are from Iben, *Annu. Rev. Astron. Astrophys.*, *5*, 571, 1967. Reproduced with permission from the *Annual Review of Astronomy and Astrophysics*, Volume 5, ©1967 by Annual Reviews Inc.)

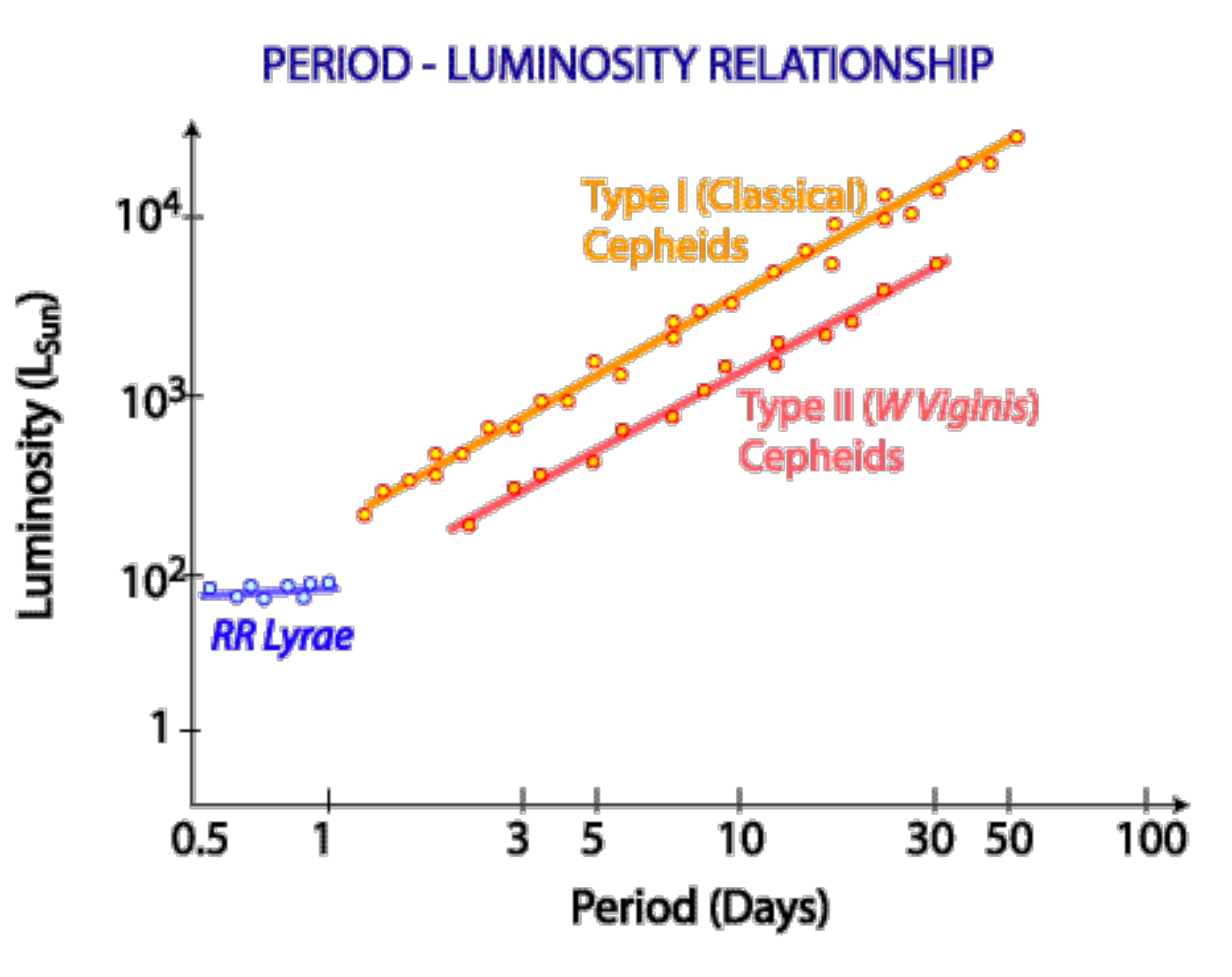


Cepheids Variable Stars

Period-Luminosity Correlation



Cepheid variables: outward pressure (P) and inward gravity compression are out of sync, so star changes size and temperature: it **pulsates**. *RR-Lyrae* variables are smaller and have pulsation periods of less than 24 hours. Also, their light curve looks different from the Cepheid light curve.



- High mass stars late in life are unstable; they overheat and cool off in a deterministic way

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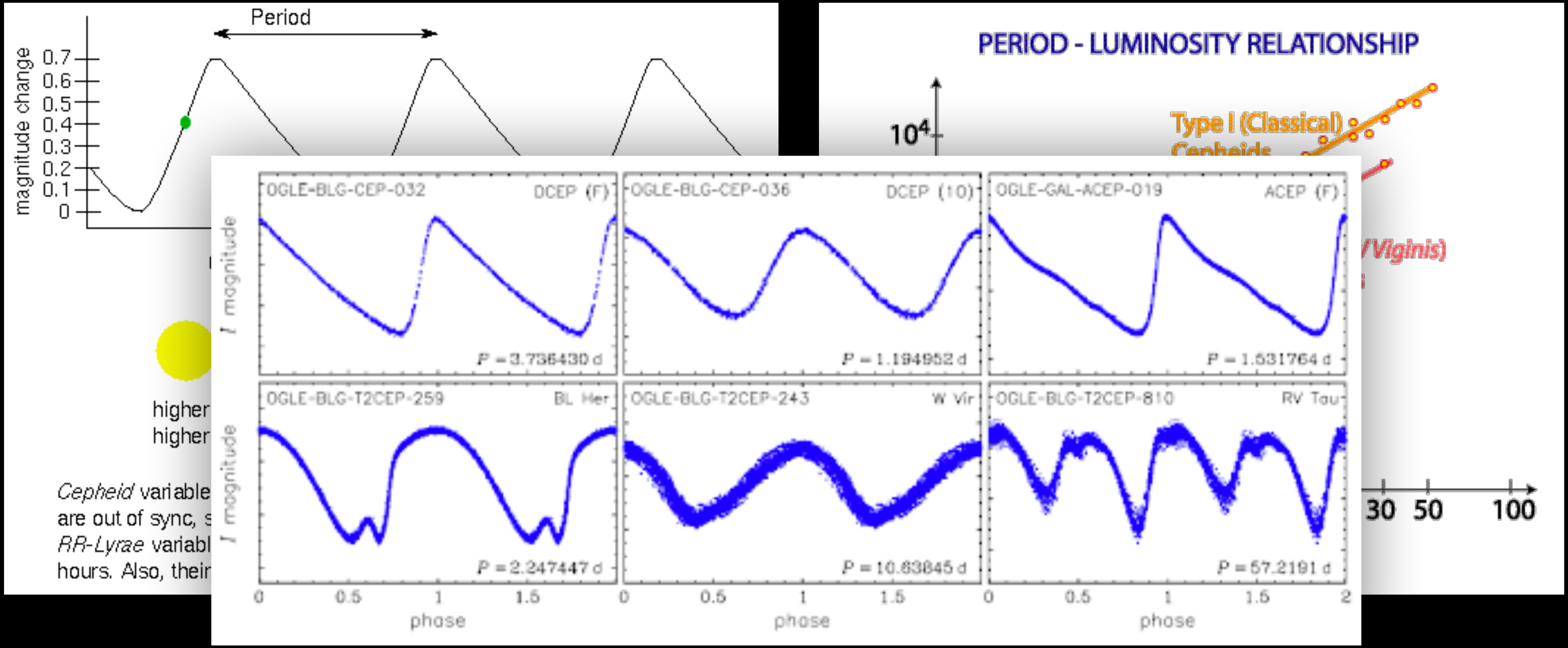

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Galaxies

Finishing The Historical Narrative

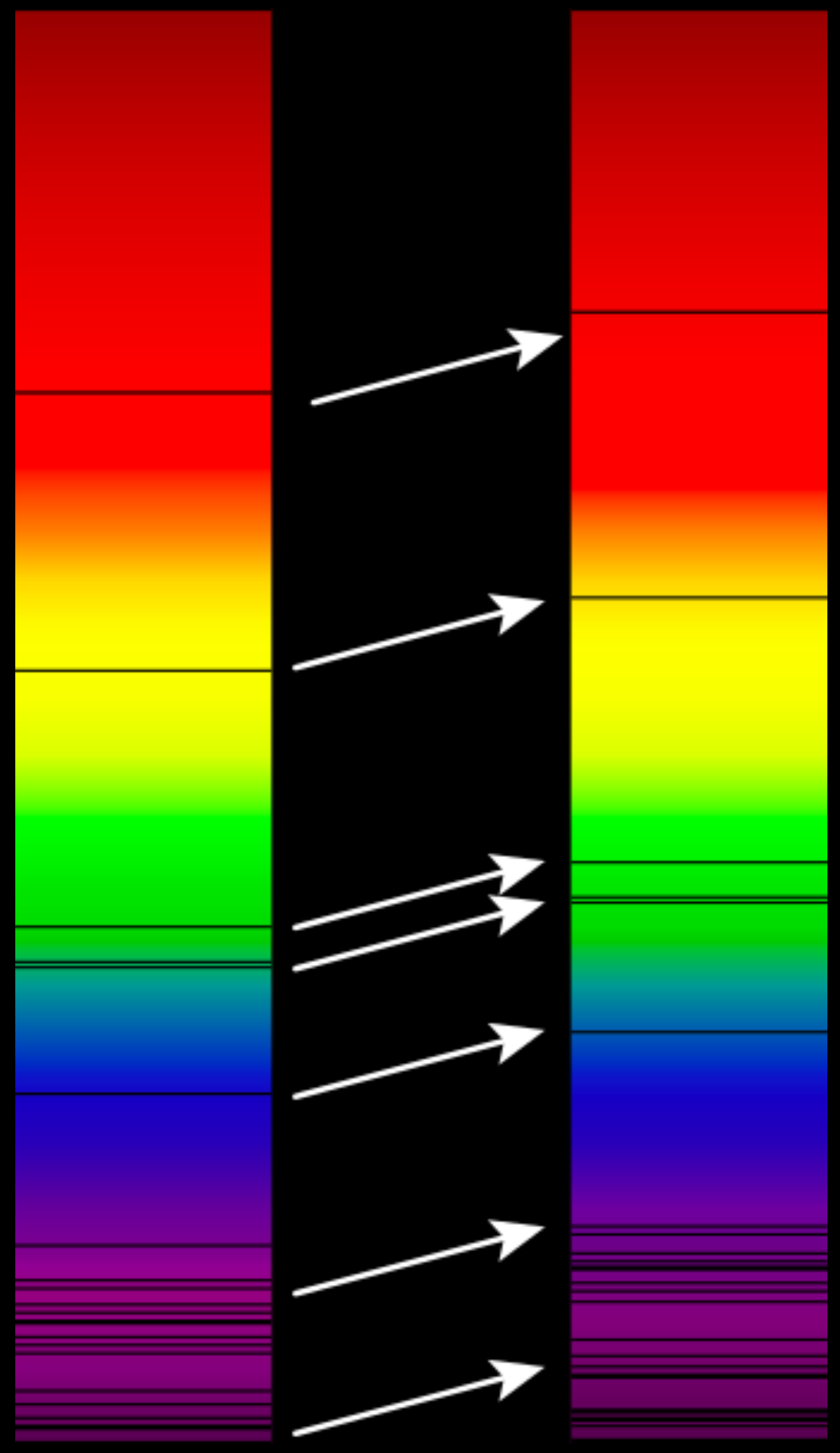
Redshift

Measuring Radial Velocity

- As telescopes and imaging technology improve, measurements of spectra (intensity as a function of light wavelength) using spectrographs comes into prominence.

- Relative shifts in an entire spectrum as used to measure radial velocity of objects

$$1 + z = \frac{\lambda_r}{\lambda_s} = \sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}} \approx \frac{v}{c}(v << c)$$



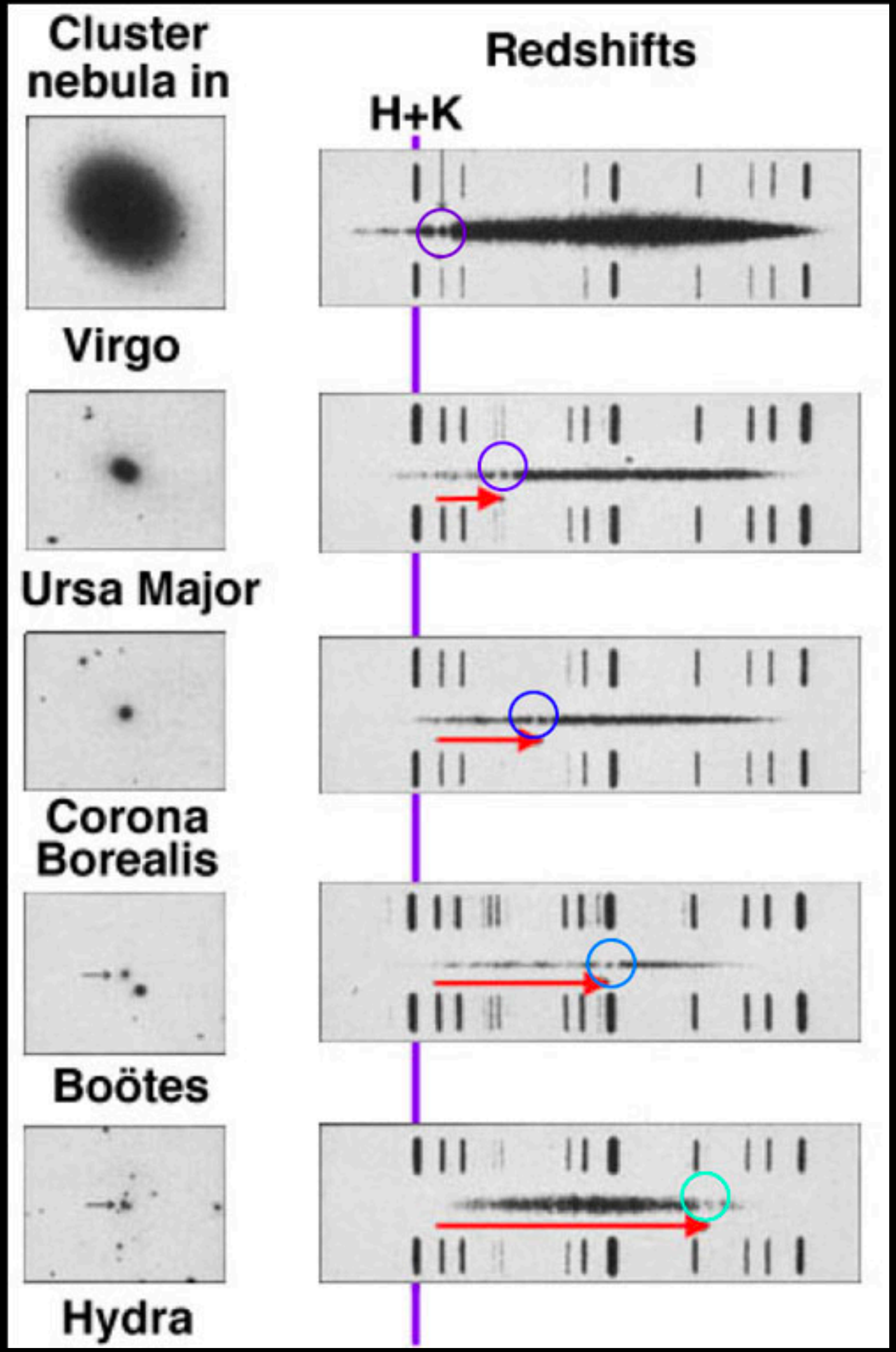
Galaxy Rotation Curves (1912-1914)

- Vesto Slipher (1914) uses this new observational tool to show that the ‘nebulae’ seen in earlier star catalogs have very peculiar properties

- The nebulae seem all to be receding at a high radial velocity from the solar system

- The majority of them can also be shown to be rotating. The magnitude of the rotation implies that, if they’re bound by gravity, they must be very large.

- More evidence, including observation of faint novas in these objects, suggests an extragalactic origin.



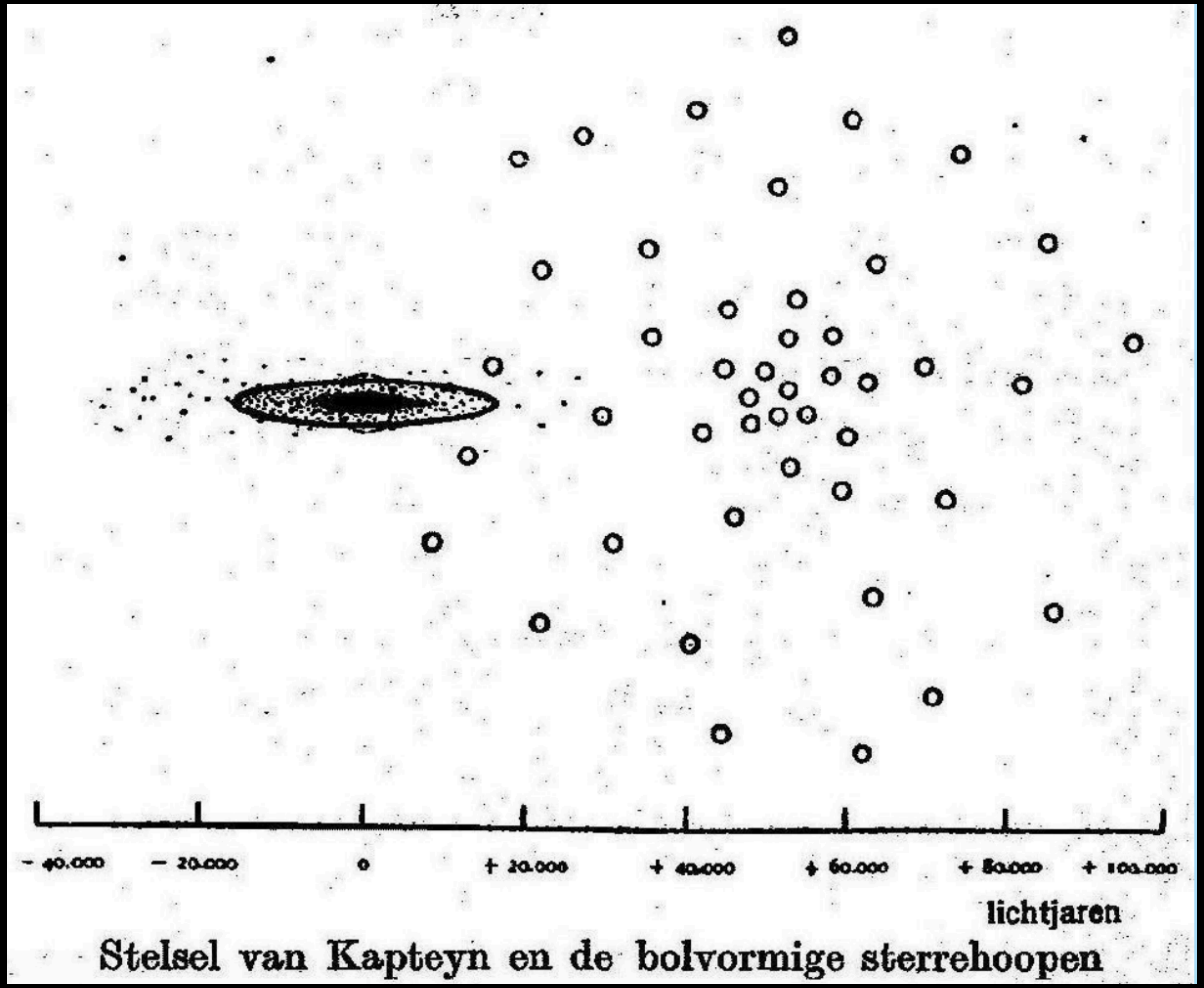
Great Debate (1920)

Curtis v Shapley

- Meanwhile, Harlow Shapley used cepheid variable stars to measure the distance to 93 globular clusters, finding that they were centered on a distant point 15 kpc from the sun (1915-1919).

- These measurements, among others led to the ‘Great Debate’ in 1920 between Shapley, who argued that there was only one galaxy, and those studying nebulae, led by Heber Curtis, who advocated for Kapteyn’s galaxy model and a multi-galaxy universe.

- Both were right and wrong; Shapley was right about the scale of the galaxy, and Curtis was right about the fact that the many observed nebulae are extragalactic objects.



Hubble (1929)

The Birth of Cosmology

- For a group of nebulae, hubble measured both redshift *and* distance, using variable stars.

- He showed that the proper motion was correlated with distance, and that all of the nebulae in his sample were much further away than Shapley's globular clusters

- Hubble's primary finding implies that the universe is expanding; this is one of the main empirical observations that gave birth to the field of cosmology, the study of the evolution of the universe

    - Only a few years earlier, Einstein had introduced a 'cosmological constant' to general relativity to enforce a static universe…so this was a novel idea

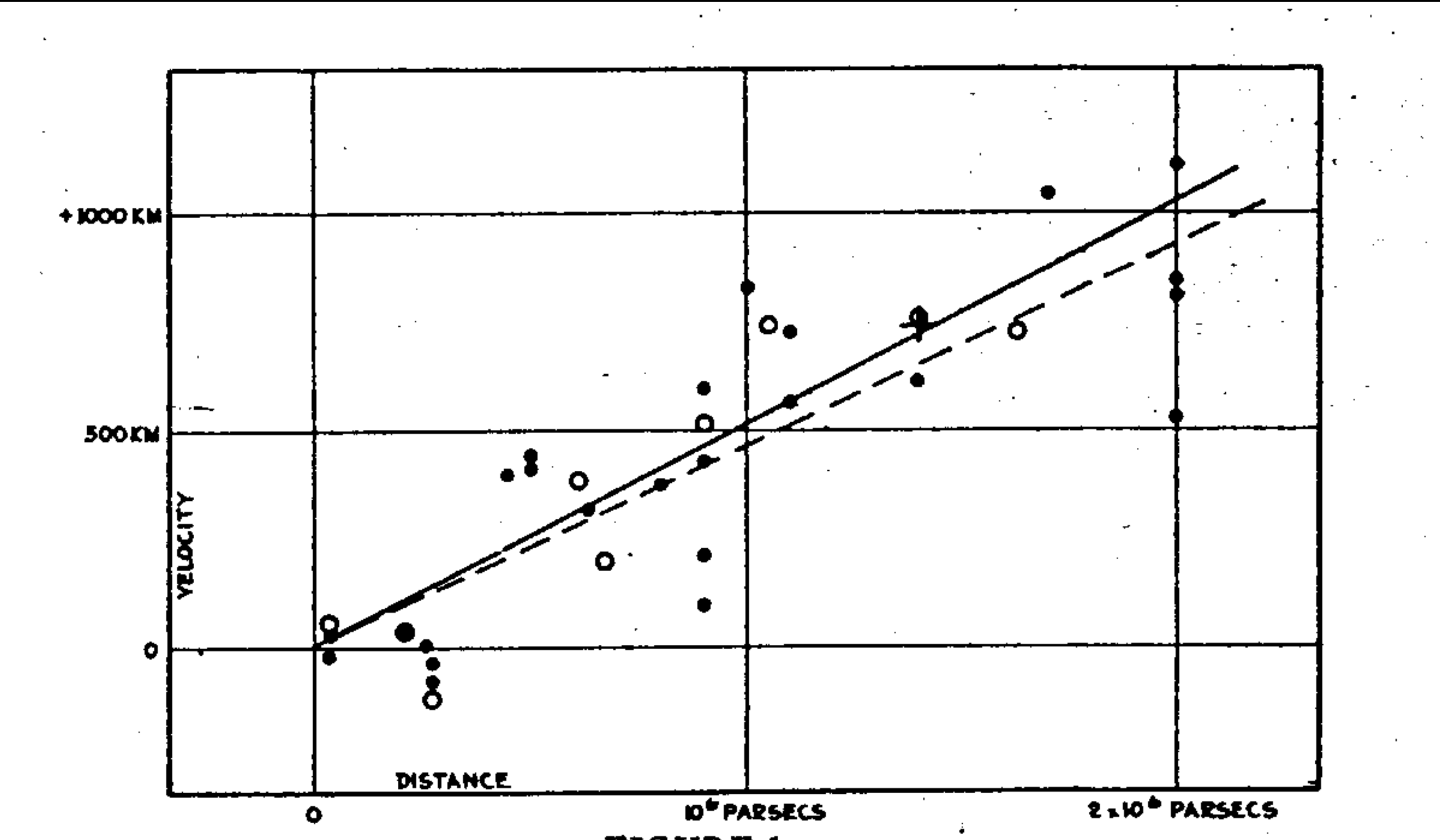
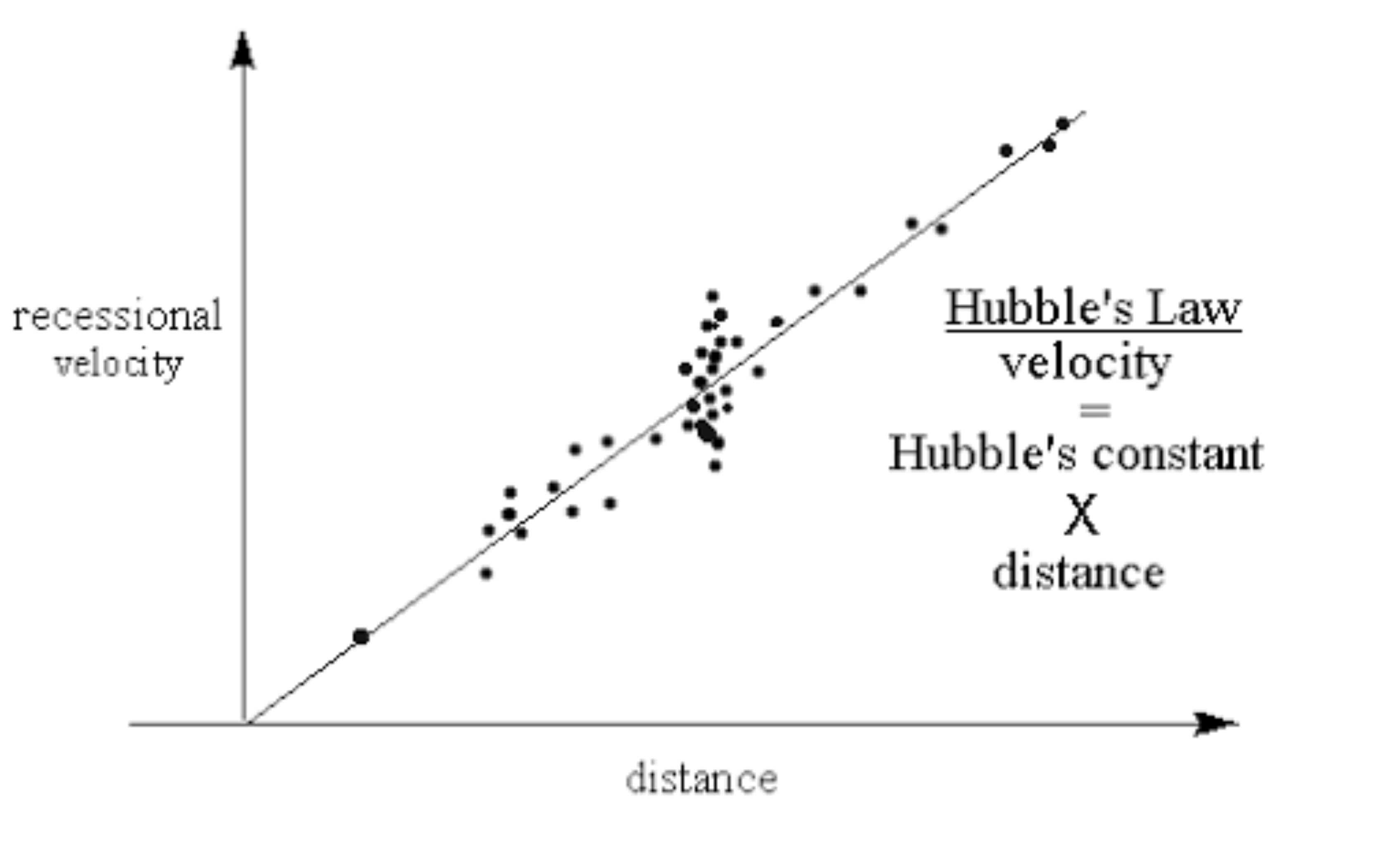
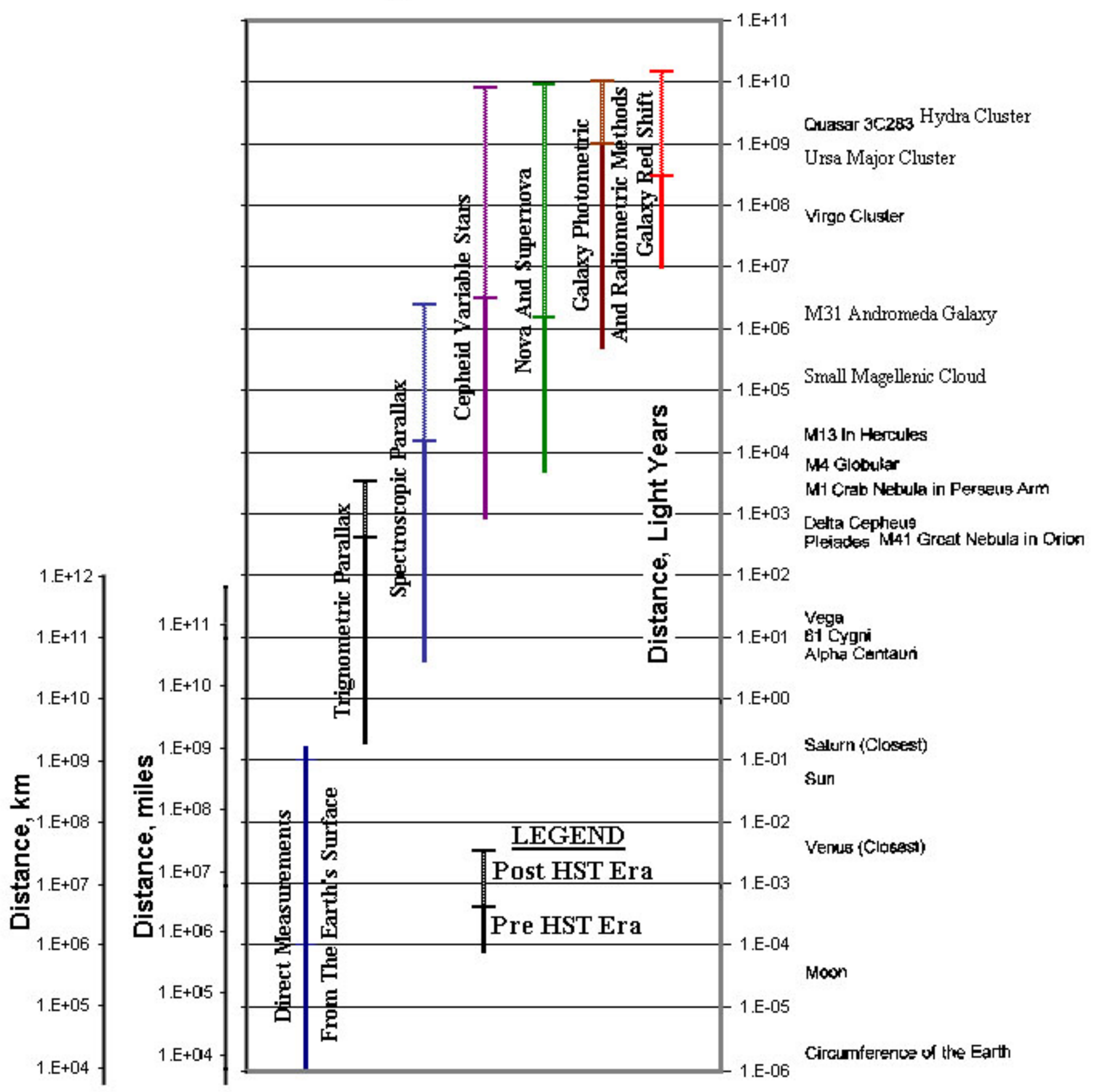


FIGURE 1



Finding Your Place In The Universe

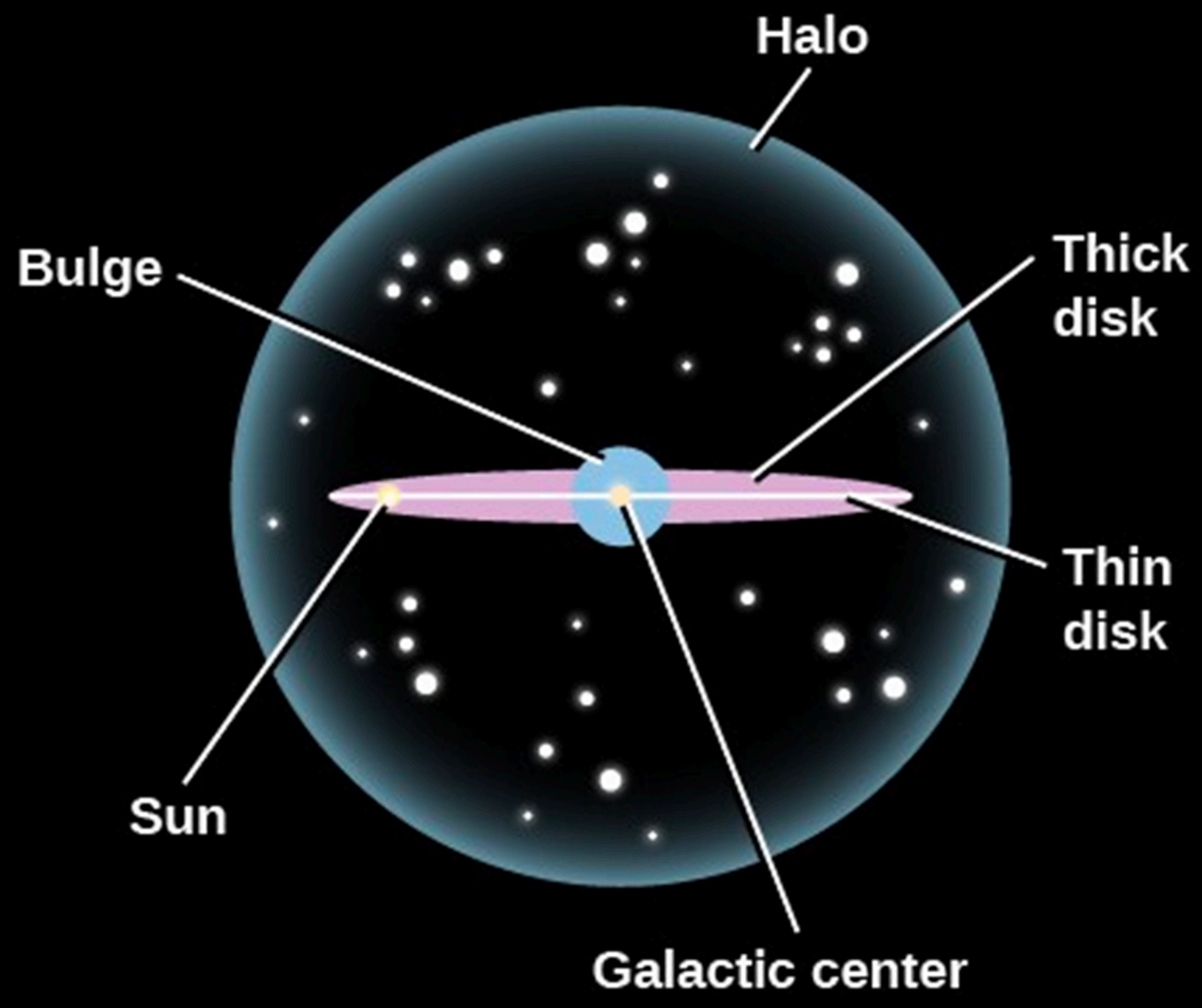


Milky Way Structure

- Our current view of the milky way is shaped by parallax measurements locally and variable stars beyond the range of parallax

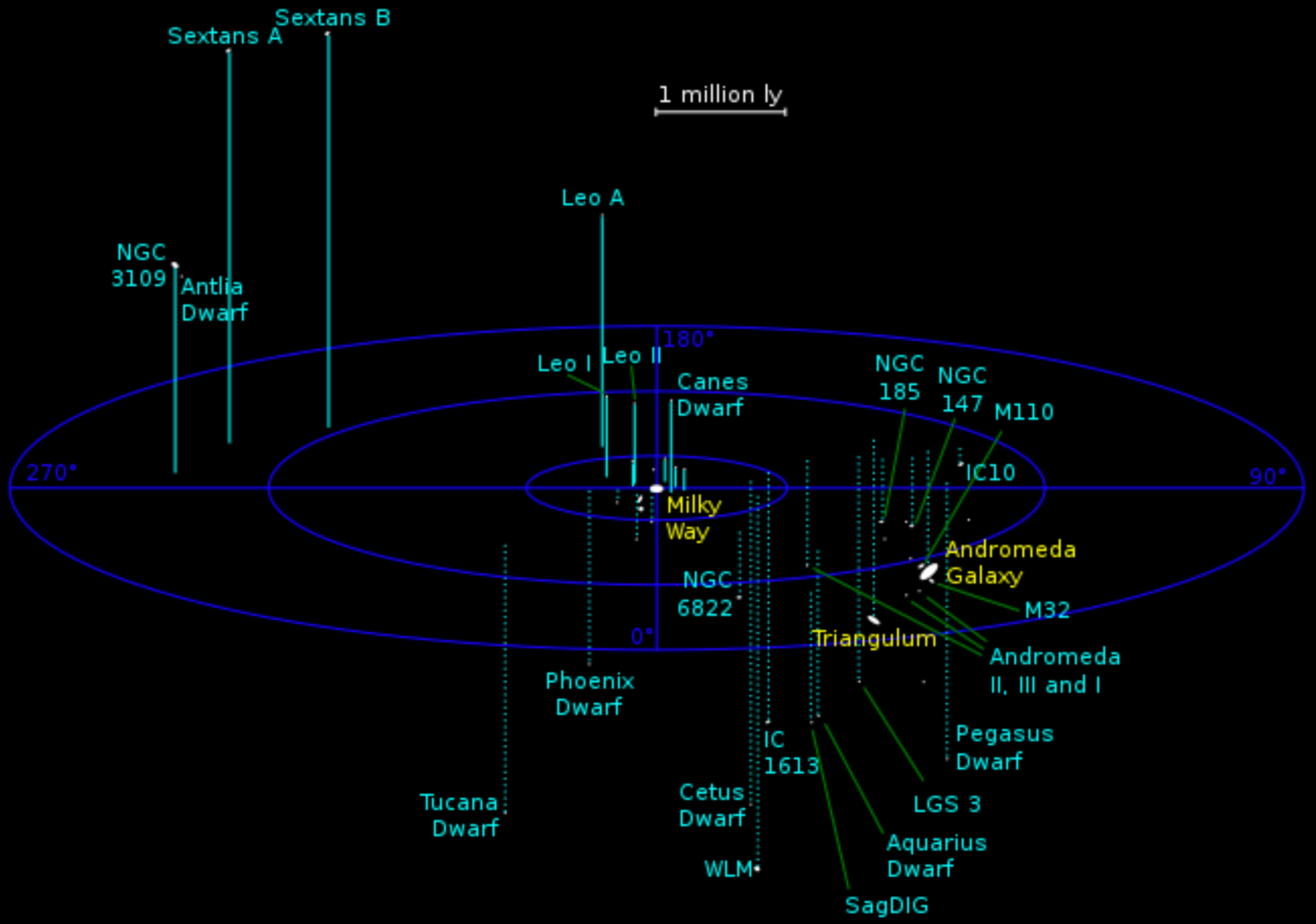
- Our galaxy, and all galaxies, have a central bulge surrounding a supermassive black hole (millions to trillions the mass of the sun)

- Components further from the plane and bulge are less gas rich and contain older stars



Local Group

The Galaxies in our Neighborhood



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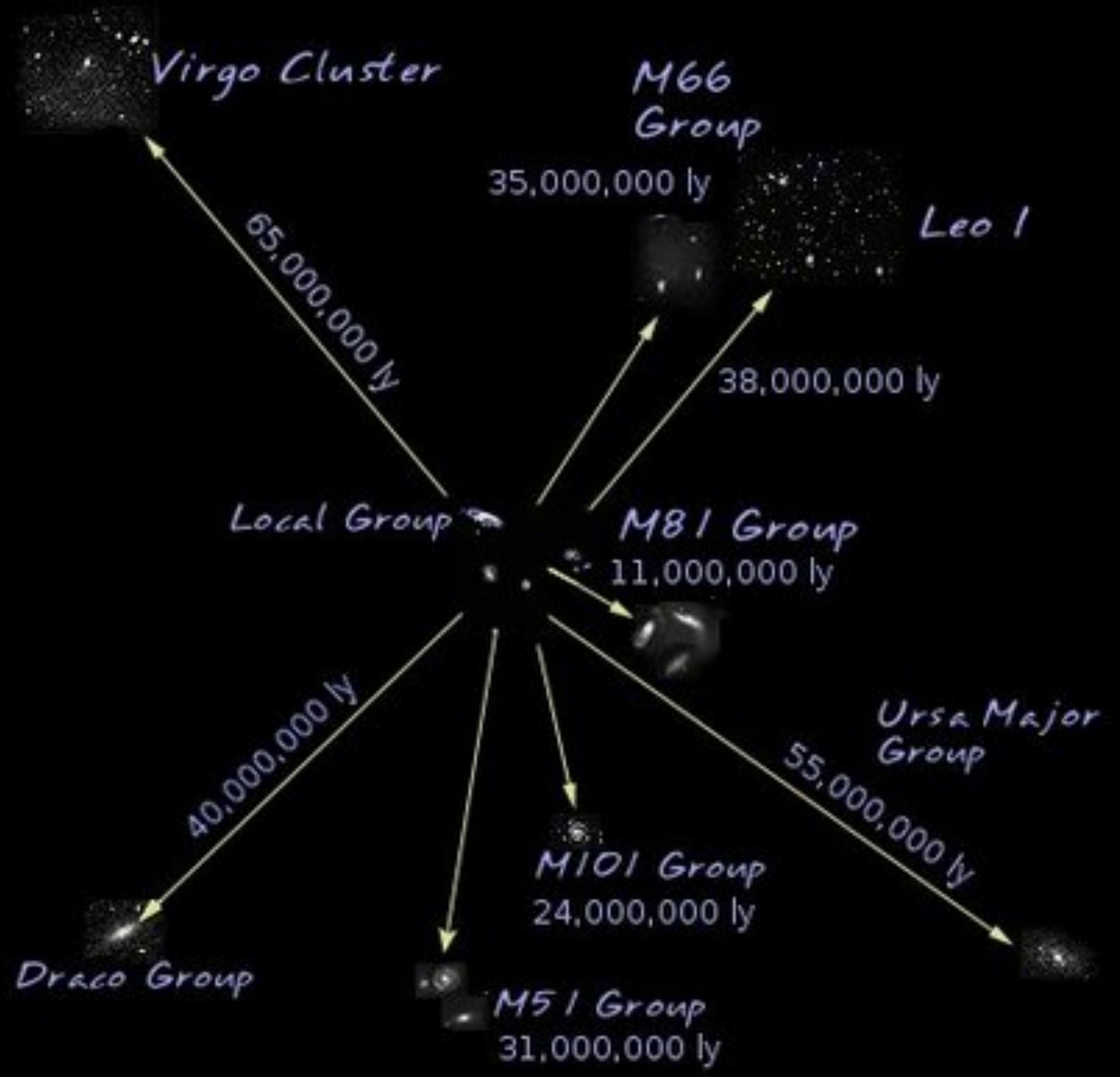
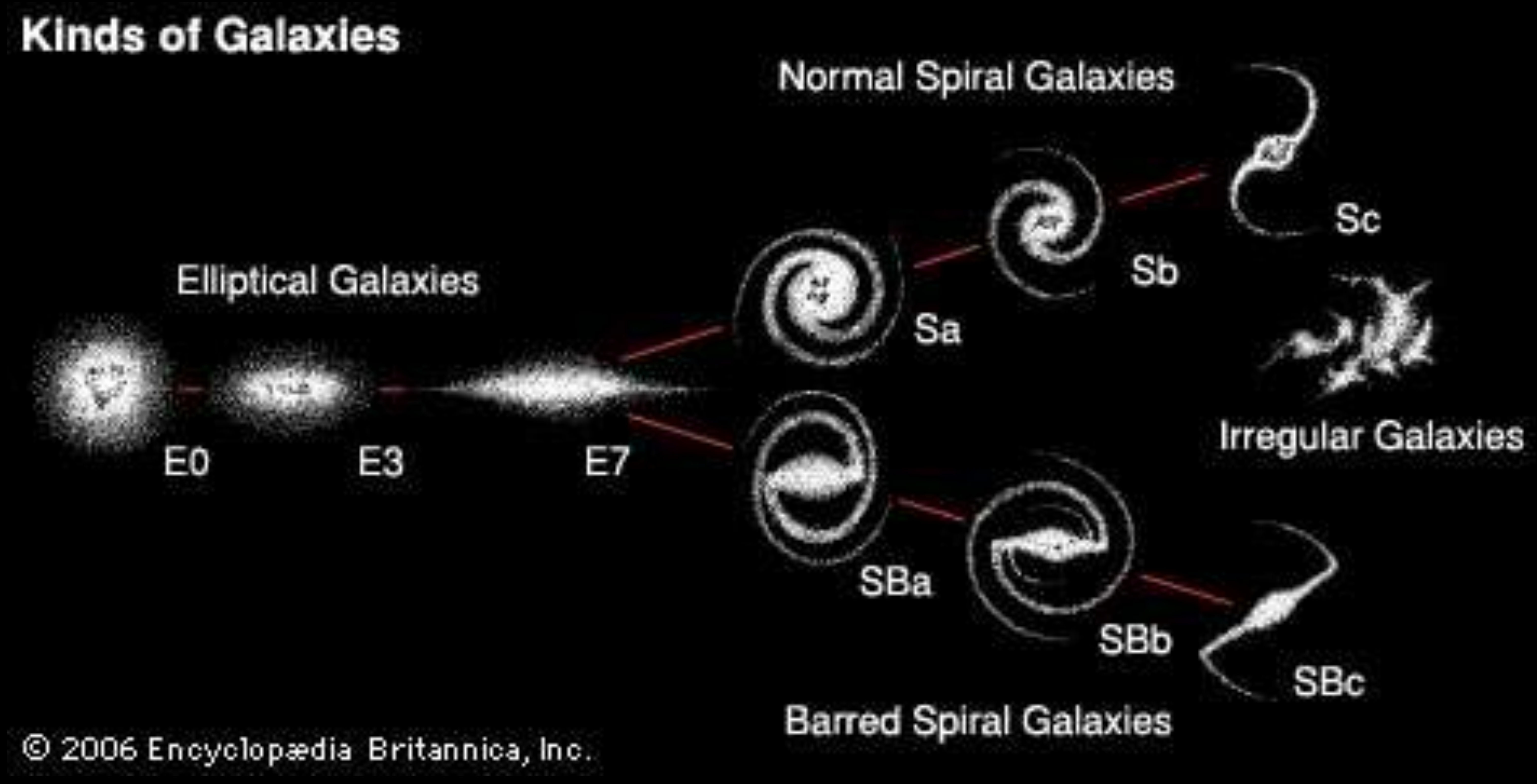


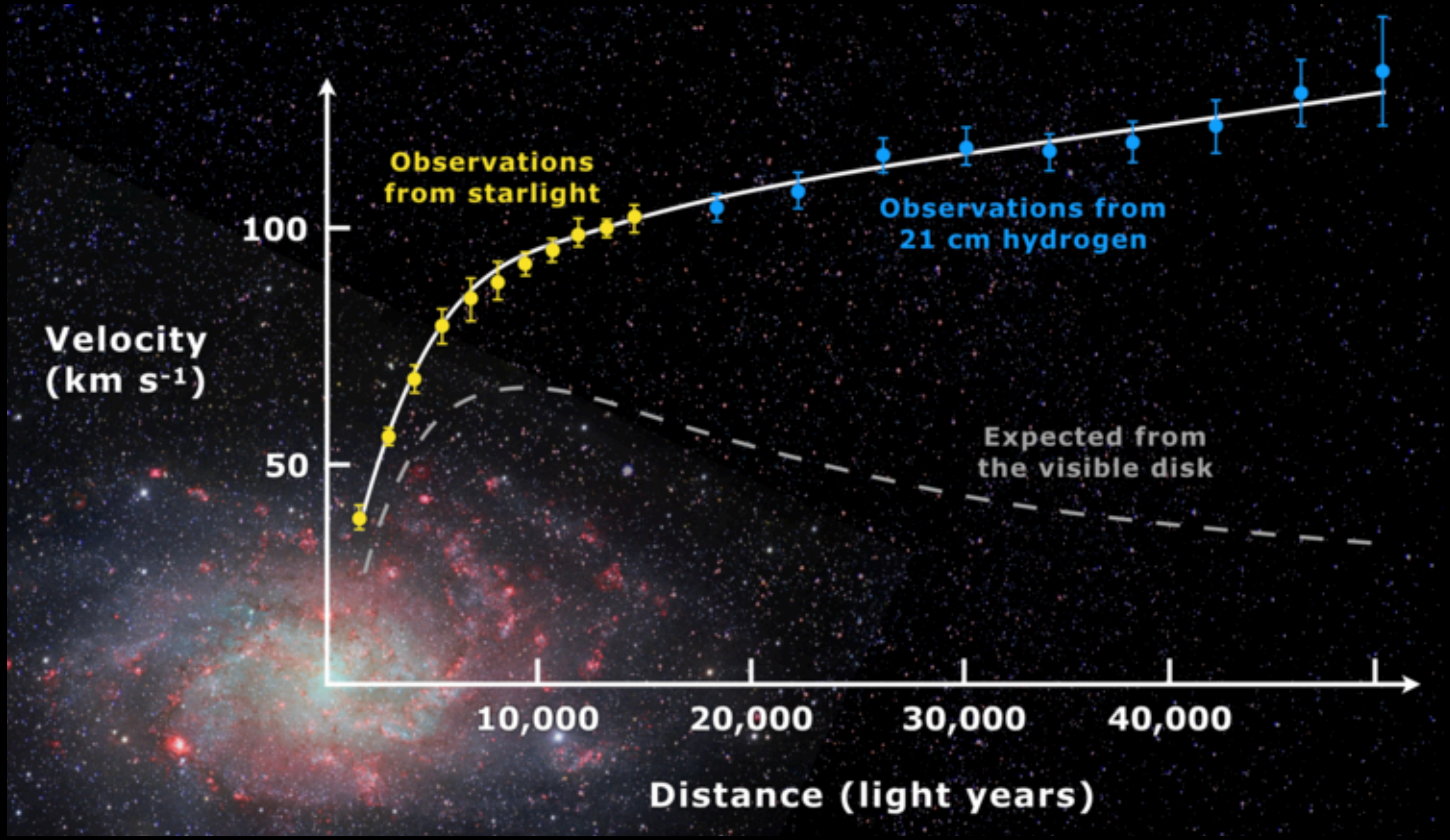
Galaxy Types

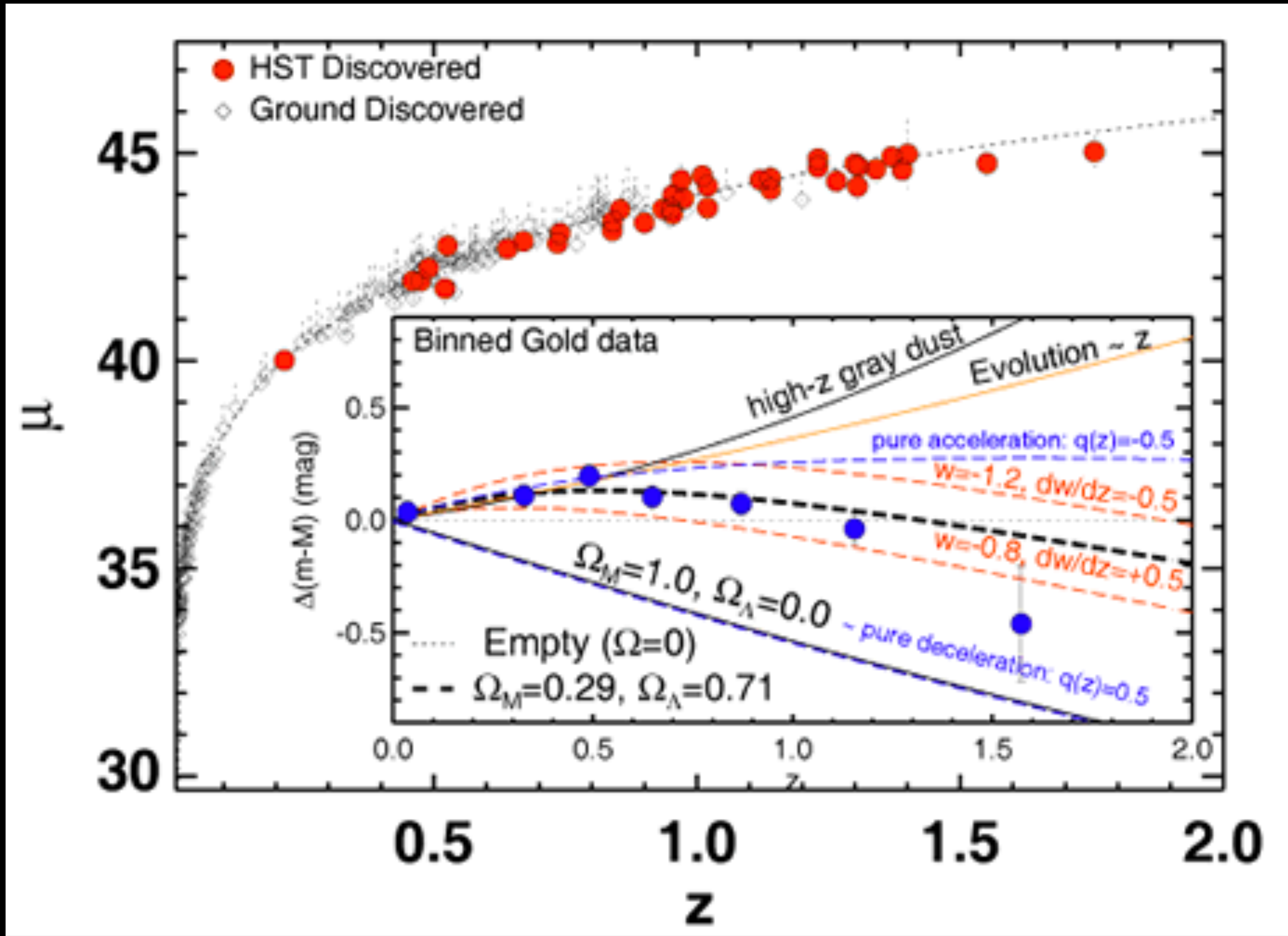
Hubble Classification



- Broadly broken into spirals and ellipticals
- Evolution proceeds from right to left! This is a historical convention.

Dark Matter and Dark Energy





- There are still lots of outstanding problems in astrophysics!

Thanks for Listening!

- Hopefully now you have a general feel for the different research which falls under the umbrella of astrophysics, and in general, how it differs from astronomy

- Extraterrestrial systems can teach us a lot about fundamental physics! The astrophysics department at Fermilab is a group of physicists using the cosmos to probe the nature of matter and energy.

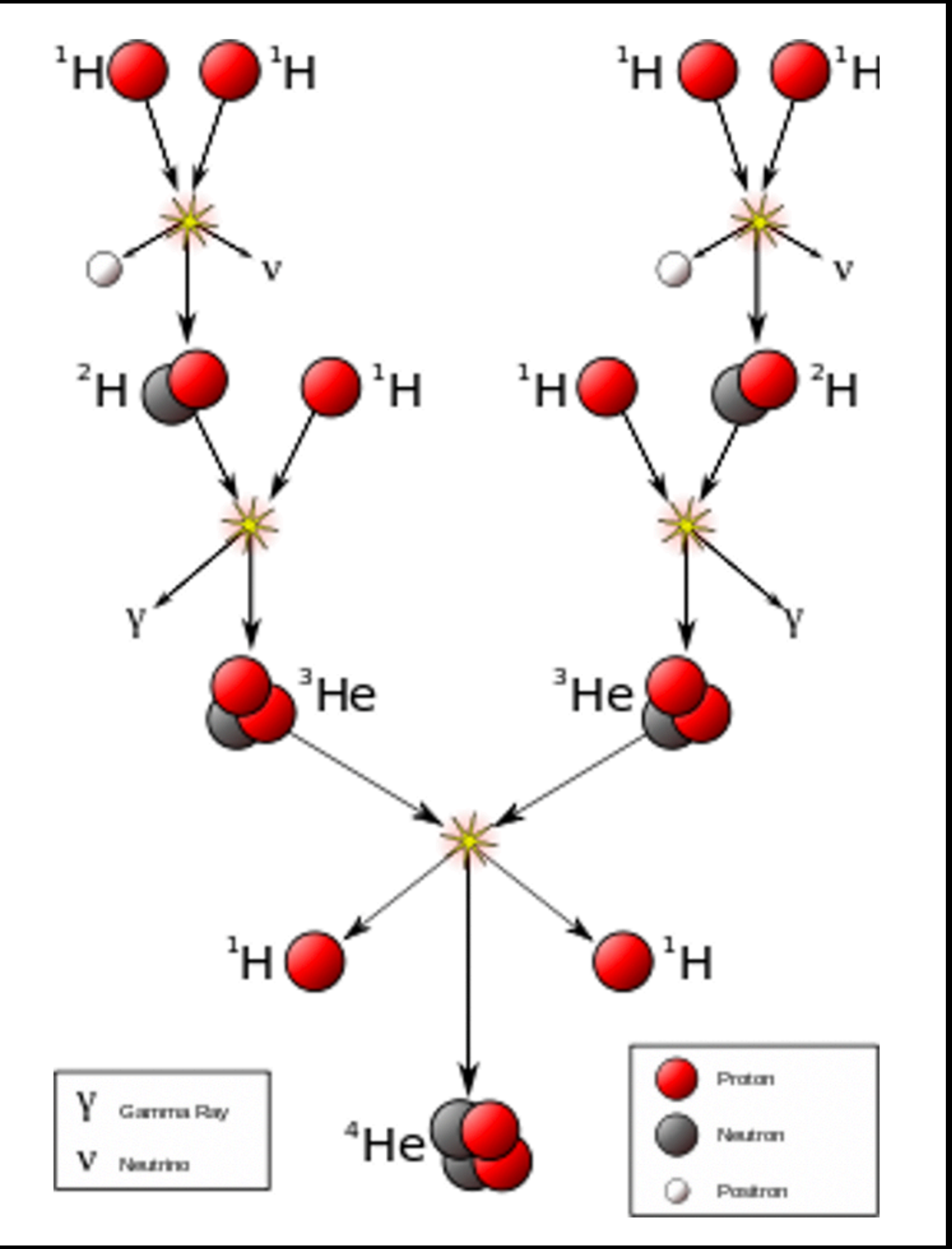
- More questions welcome (or email me, kurinsky@fnal.gov)

- Useful resources:
  - An Introduction to Modern Astrophysics - Carroll & Ostlie
  - “A History of Dark Matter” - Bertone & Hooper
  - The House of Wisdom: How Arabic Science Saved Ancient Knowledge and Gave Us the Renaissance - Jim Al-Khalili
  - Finding Our Place in the Universe - Helene Courtois
  - A Brief History of Time - Hawking

Backup

Fusion Processes

- Hydrogen Burning
  - PP Chain - turning hydrogen into Deuterium and Helium
    - 4H -> 1 He



Fusion Processes

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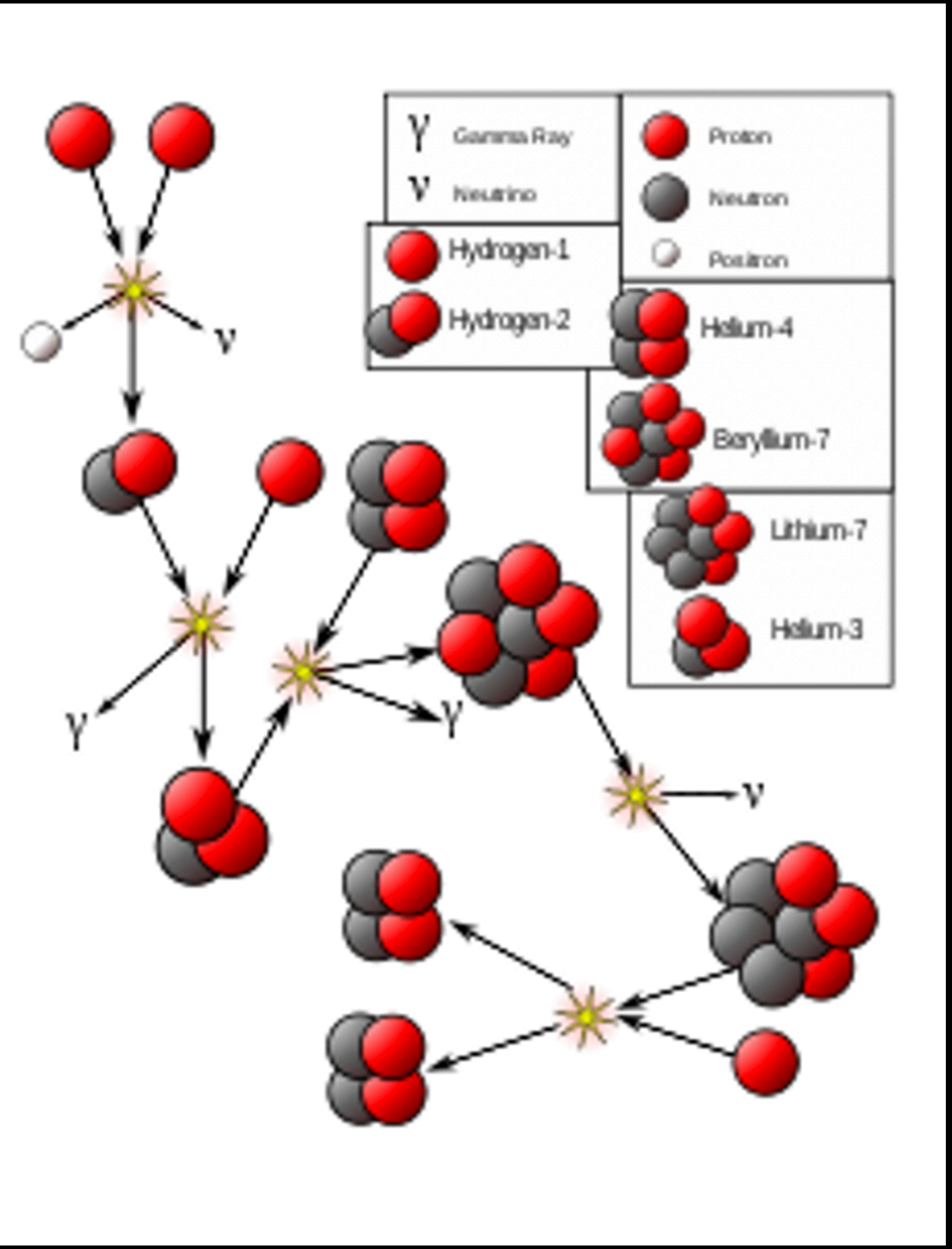
    - I, II, III



Fusion Processes

- Hydrogen Burning
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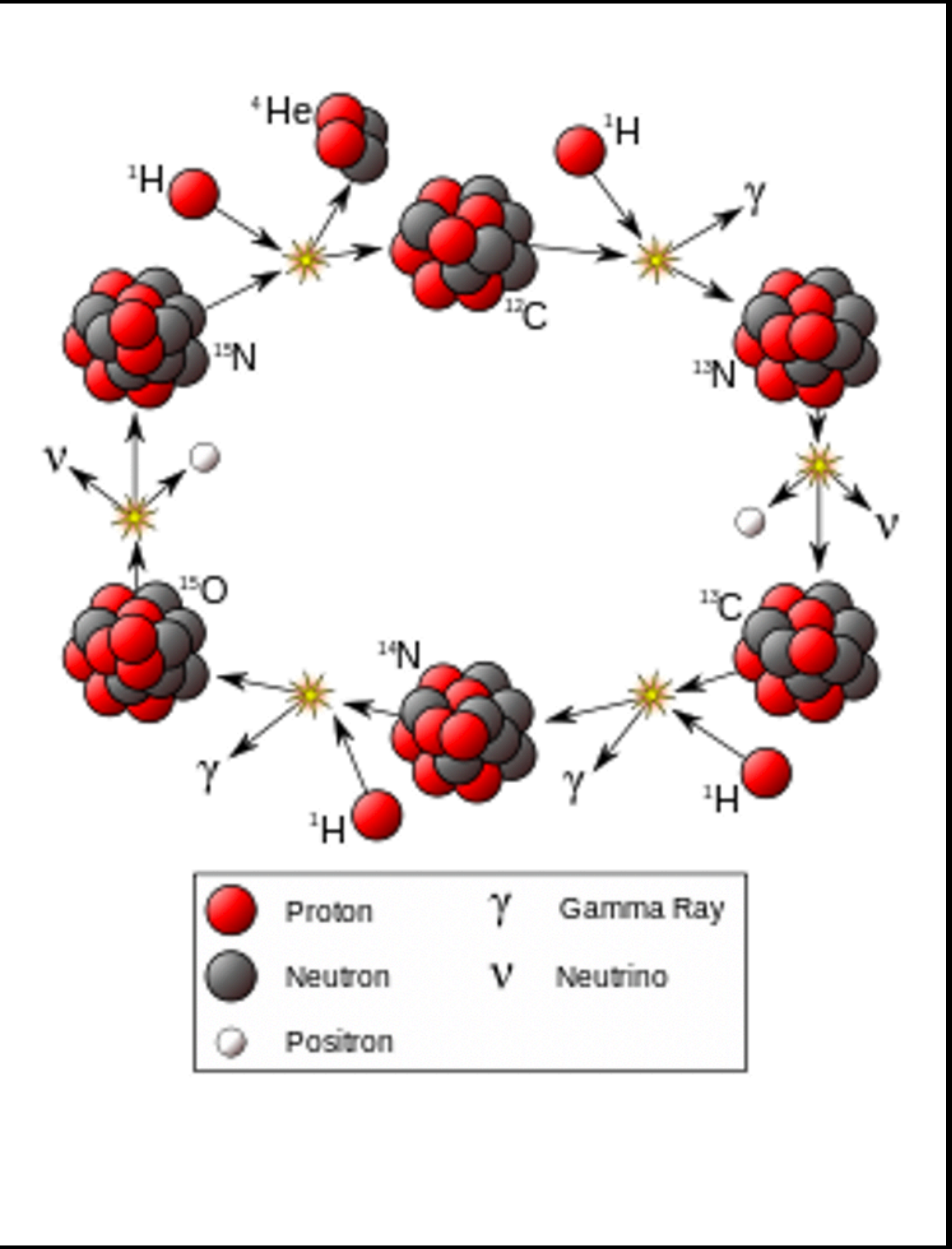
    - 4H -> 1 He
    - I, II, III
  - CNO Cycle - once enough carbon is present, at high temperatures, carbon is used as a catalyst to generate nitrogen, oxygen, and helium



Fusion Processes

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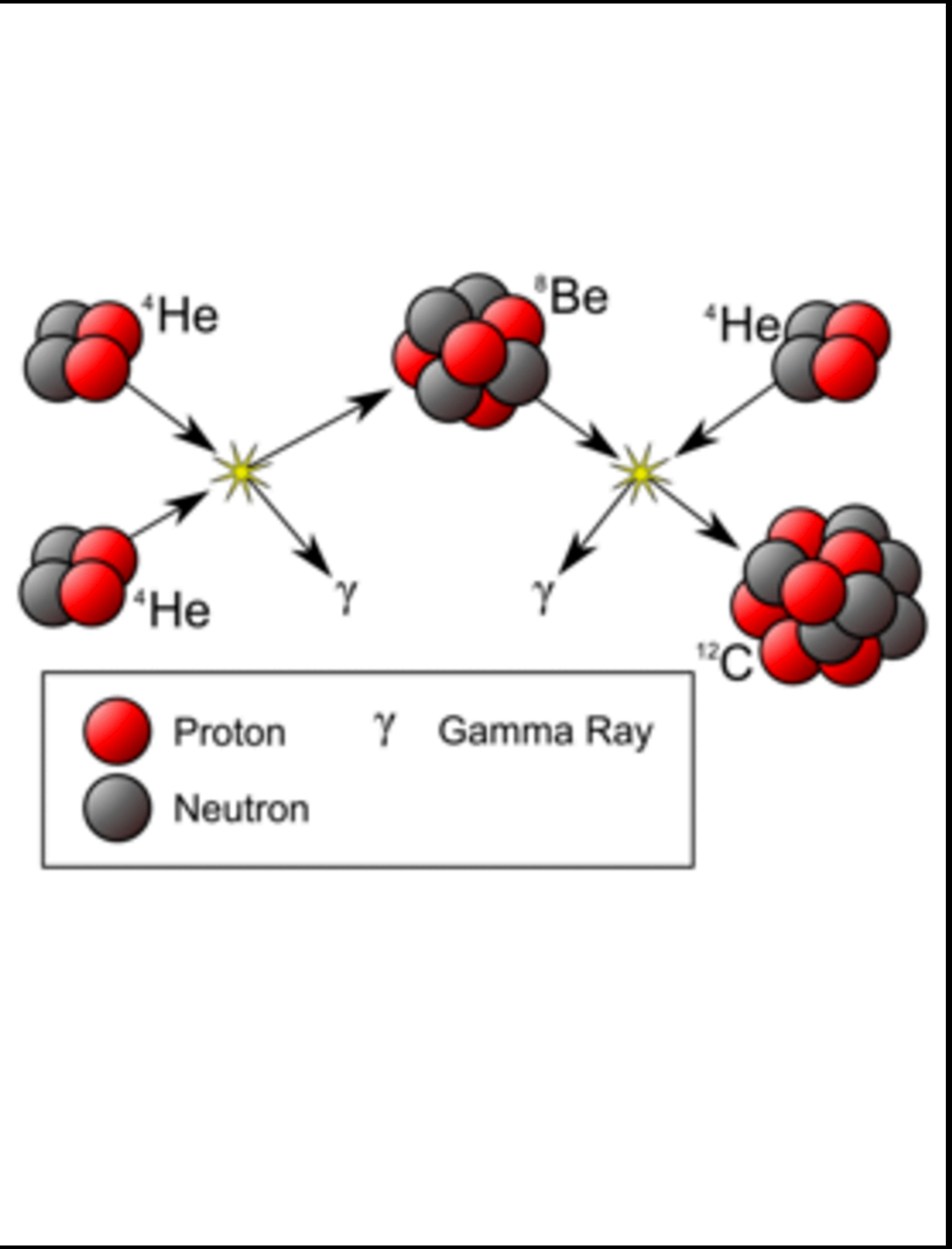
- Helium Burning
  - Triple Alpha Process (3He -> C12)
  - Alpha Ladder (He + X)



Gravitational Waves

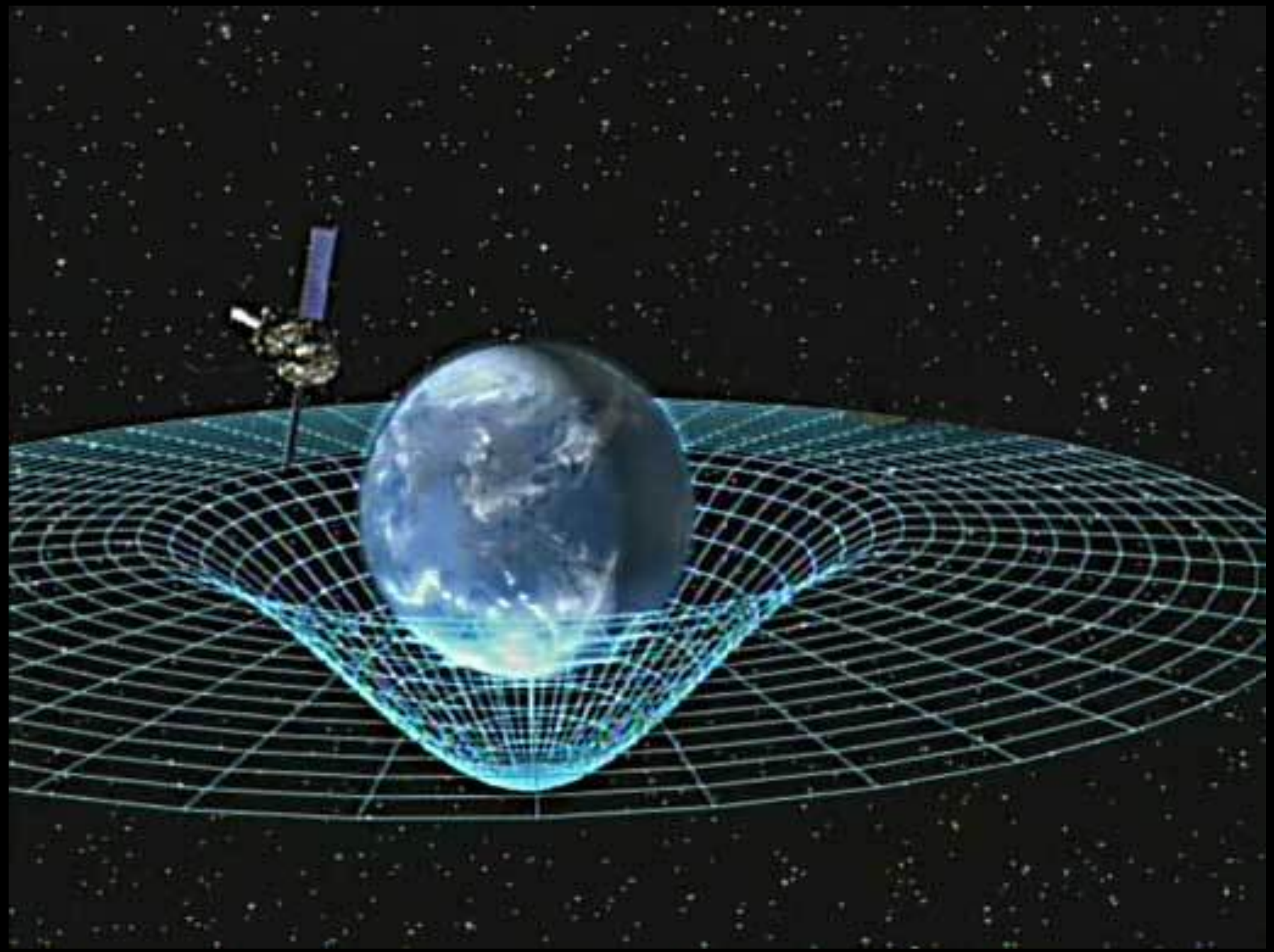
What are Gravitational Waves

- Gravitational waves are called ‘Ripples in Spacetime’; they are wave-like distortions in space generated by changes in all gravitational fields

- Everything generates gravitational waves, even you! But they are so small for most object (gravity is fairly weak, after all) that we can only detect the largest ones.

- These waves work exactly the same way as ripples in a pond. Because gravity travels at light speed, the history of changes in the gravitational field ripple out from the center of the change.

- We can now detect these (as of 2 years ago) using the Laser Interferometer Gravitational Wave Observatory (LIGO)



How Much do Gravitational Waves Affect Spacetime?

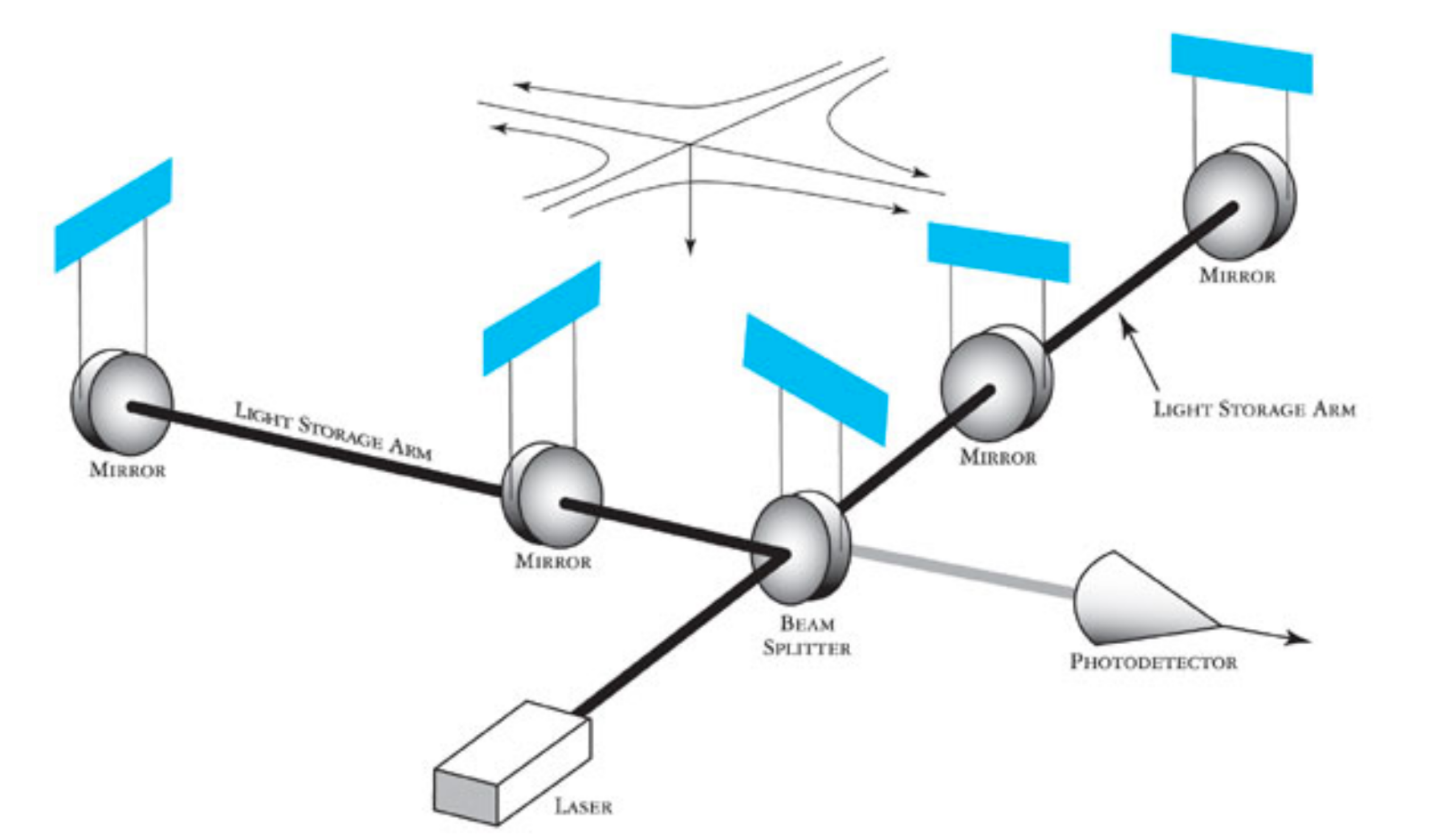
- Because gravity waves distort distances, we want to figure out how large those distortions are from some standard distances. The strain, which is produced by the wave, is the fractional change in length produced by a wave:

$$h = \frac{\Delta L}{L} = \frac{64\pi^2 G}{Rc^4} M \frac{r_0^2}{T^2}$$

  where G is the gravitational constant ($6.67*10^{11}$ N*m^2/kg^2), M is the total mass of the system, R is the distance to the system, r_0 is the orbital radius and T is the orbital period.

- What is the strain produced by:
  - The earth sun system?
  - A binary neutron system where each star is 1 solar mass ($3*10^{30}$ kg), orbital period is 1 ms, and orbital distance is ~ 20 km?
- Suppose I measure an object 4 km long; what distance change is this? What if I measure an object 40,000 km long?
- We only observe catastrophic events because they produce the largest strains!

Detecting Gravitational Waves

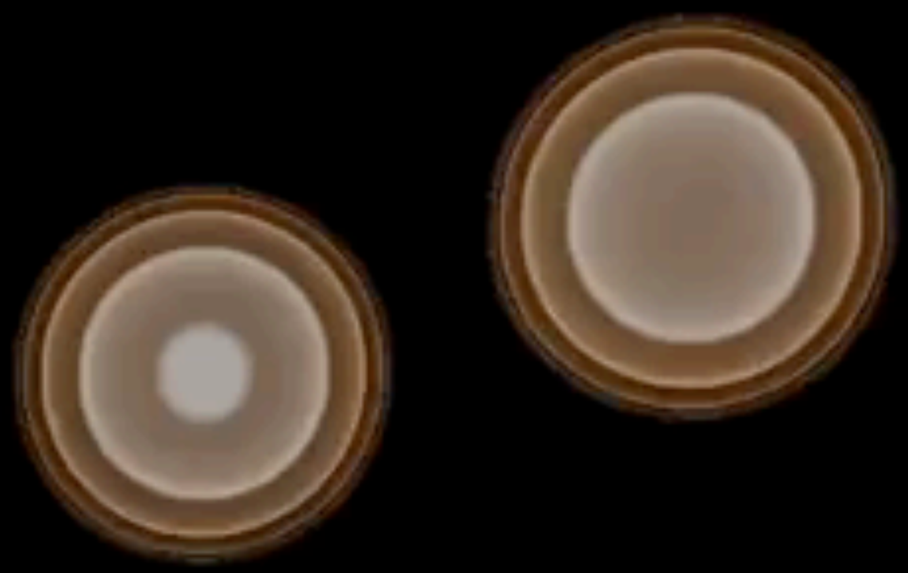


- Spacetime is distorted, changing the transit time of light between the corner and ends of the arms. Speed doesn’t change, but the light is either traveling slightly shorter or longer distances. Comparing the travel times gives the difference in the effective arm length.

- The wave is polarized so that one direction is stretched while the other is shrunk, and there are two polarizations called ‘+’ (along x and y) and ‘x’ (along the 45 degree lines between x and y)

- Compare the wavelength of 1054 nm light (the laser used in LIGO) to the distance change you just calculated for the change over 40,000 km. This is the fraction of wavelength distance LIGO needs to detect.

GW170817: The Merger of Two Neutron Stars

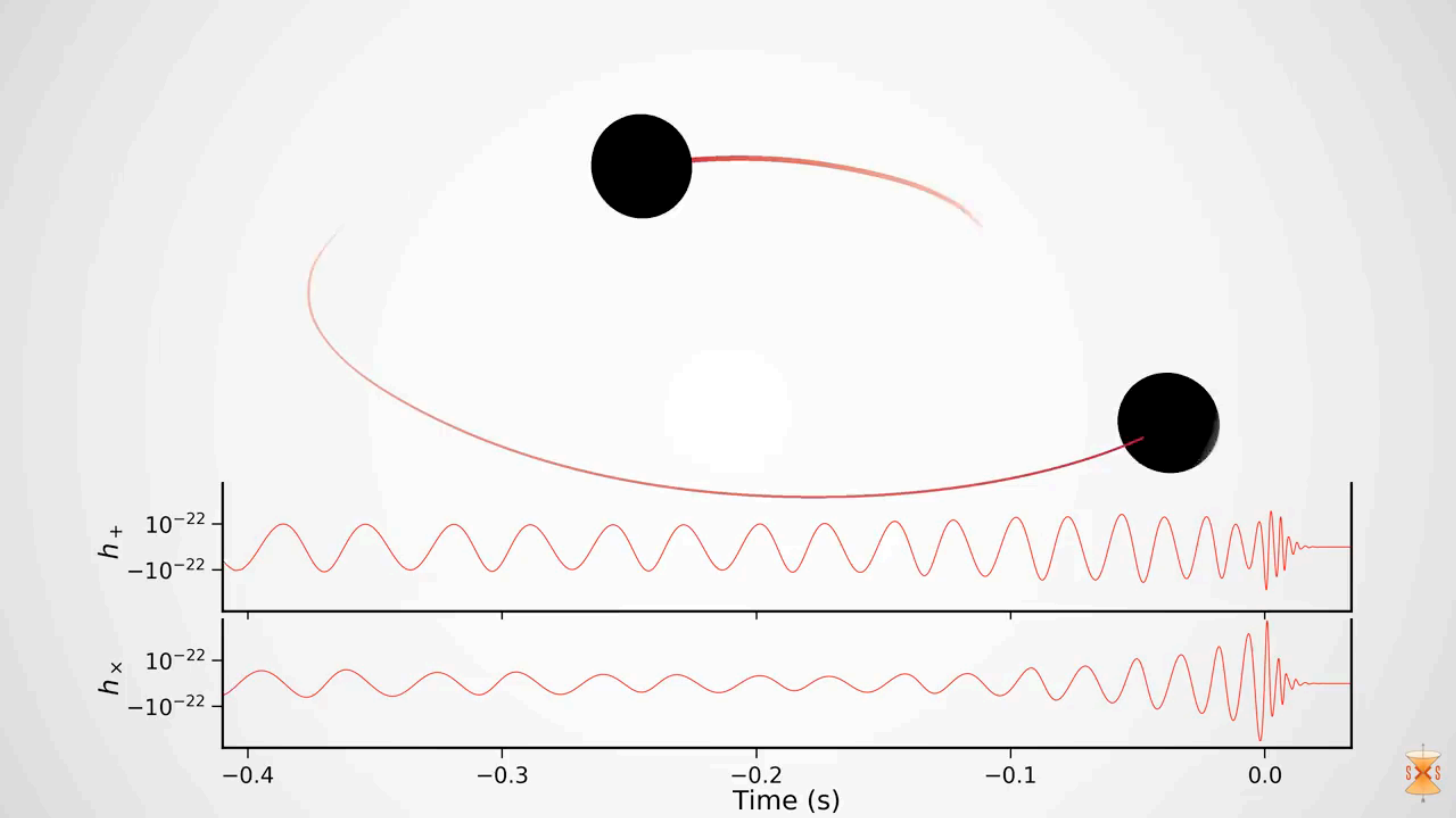


Matter Density

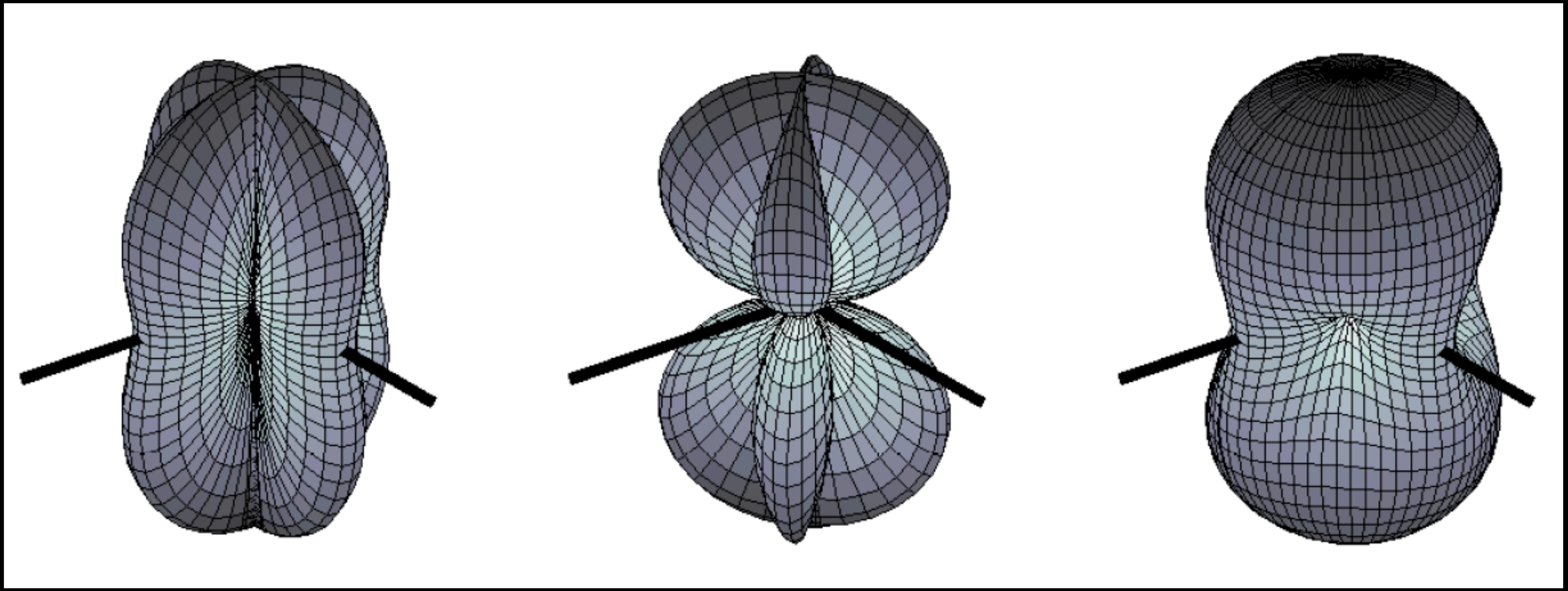
Gravitational Waves

Georgia Tech

What LIGO Sees



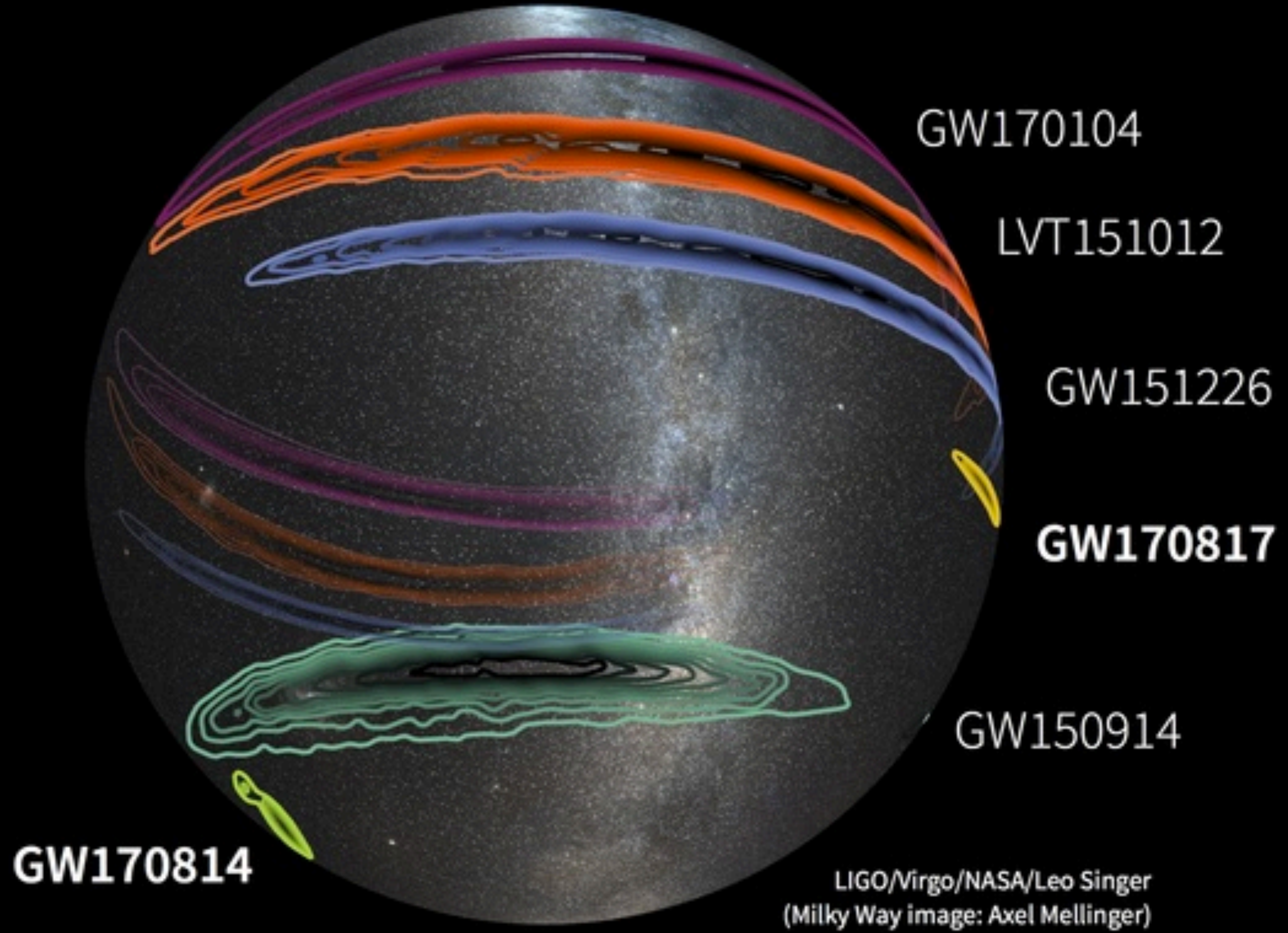
Directional Sensitivity



- Unlike a normal telescope, LIGO cannot be ‘pointed’, and a single detector cannot determine the direction of a gravitational wave. The relative sensitivity as a function of position in the sky allows multiple interferometers to triangulate the event in question

- From left to right: ‘+’ polarization, ‘x’ polarization, and mean sensitivity of the two

- The lines show the position of LIGO’s arms; it is highly sensitivity to waves perpendicular to it, and blind to a large fraction parallel to the arms


GW170104
LVT151012
GW151226
GW170817
GW150914
GW170814
LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

Gravitational Distance Ladder

- How do we know that what we're seeing are really mergers of black holes and neutron stars?

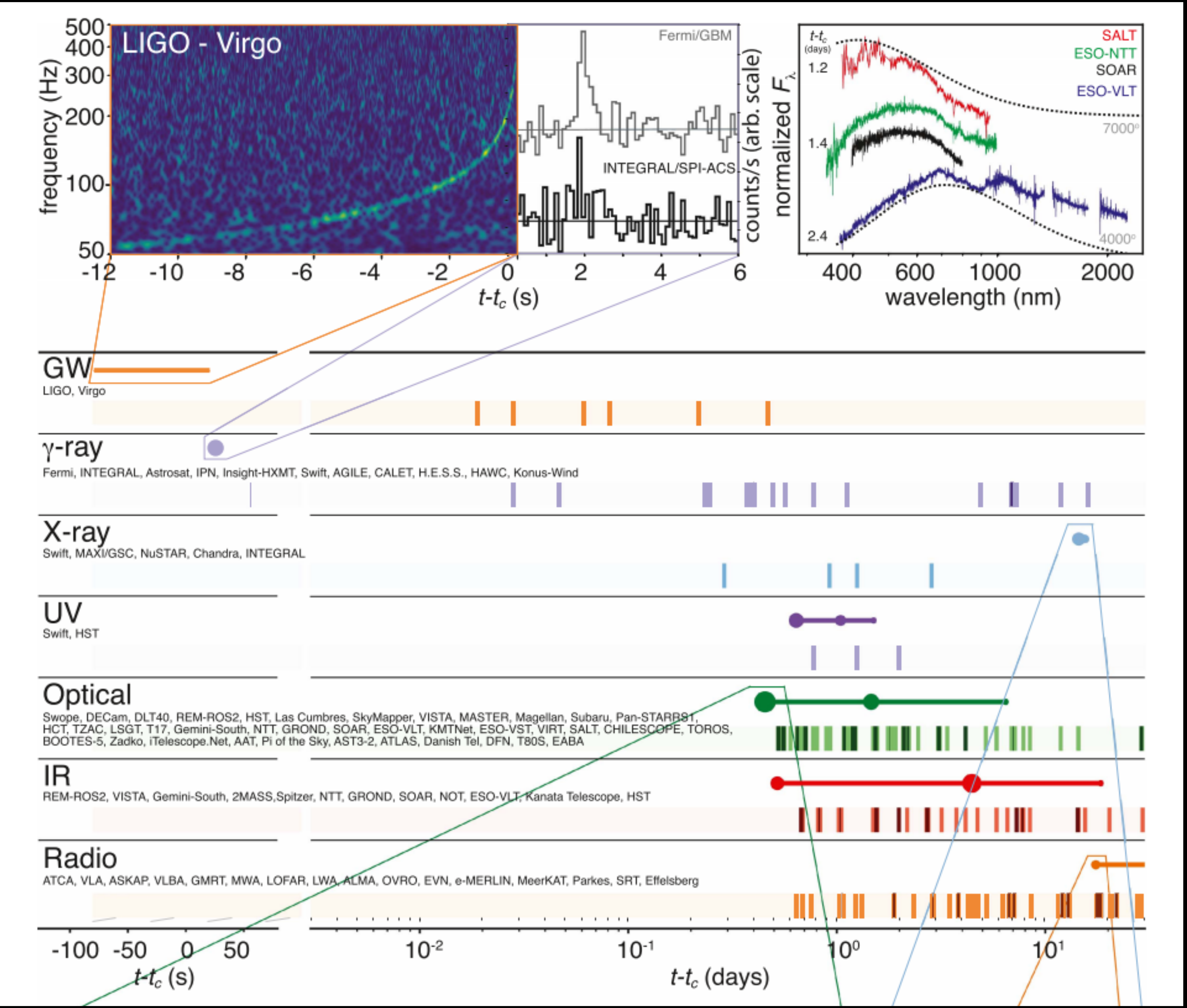
- What kinds of science are gravity waves useful for?

- Answer: LIGO/VIRGO/KAGRA/GEO (world-wide gravity wave telescope network) can send early warnings to conventional observatories to look at the immediate aftermath of these huge events

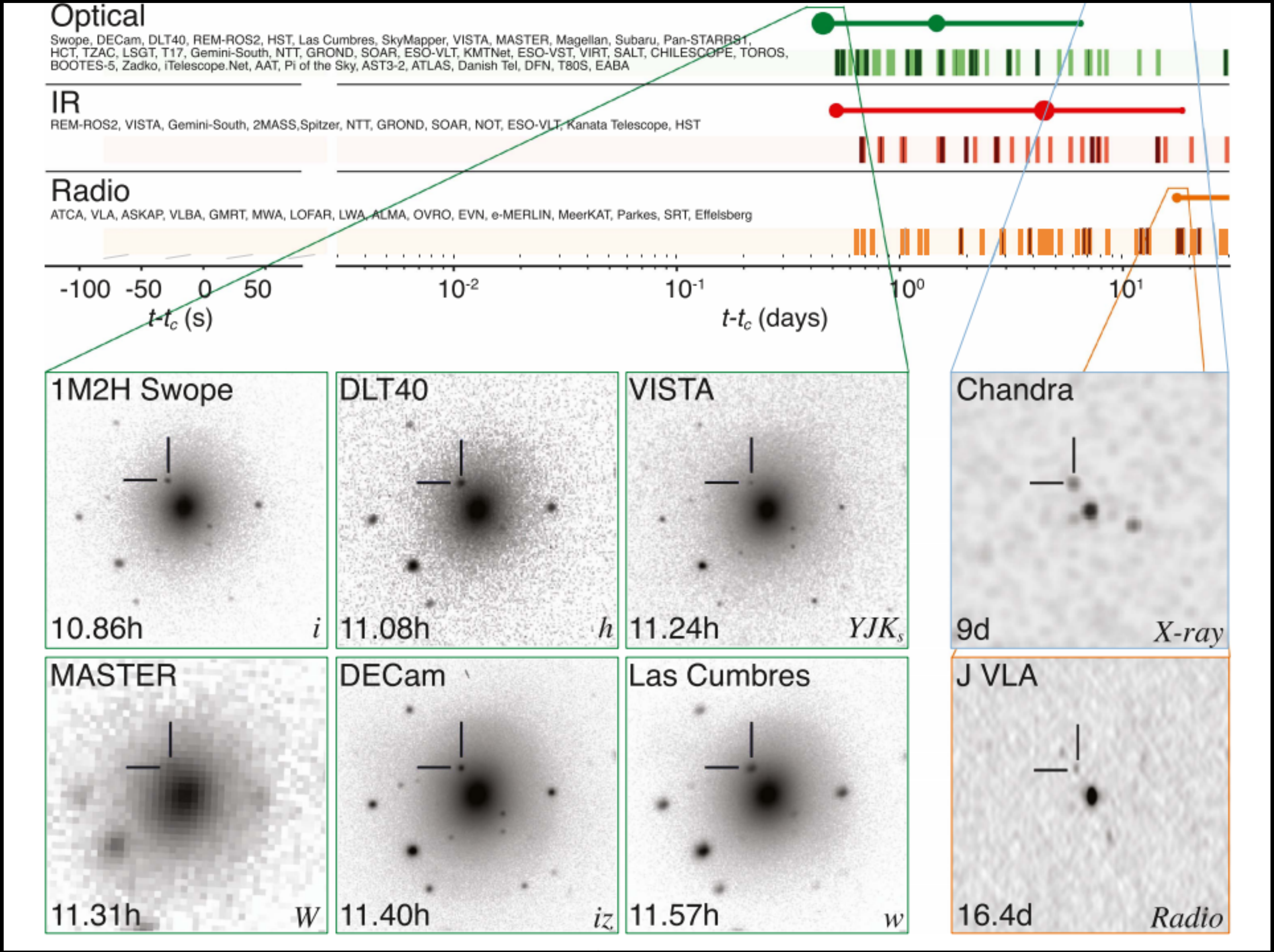
  - Gravity waves come first; nothing in the universe can slow them down.

  - Light and neutrinos produced in the aftermath of the GW event!

  - GW observatories are probing the whole sky, and can direct telescopes with small fields of view to specific areas of the sky



LIGO - Virgo
frequency (Hz)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
t-tc (s)
t-tc (days)
SALT
ESO-NTT
SOAR
ESO-VLT
7000°
4000°
normalized Fλ
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
t-tc (s)
t-tc (days)



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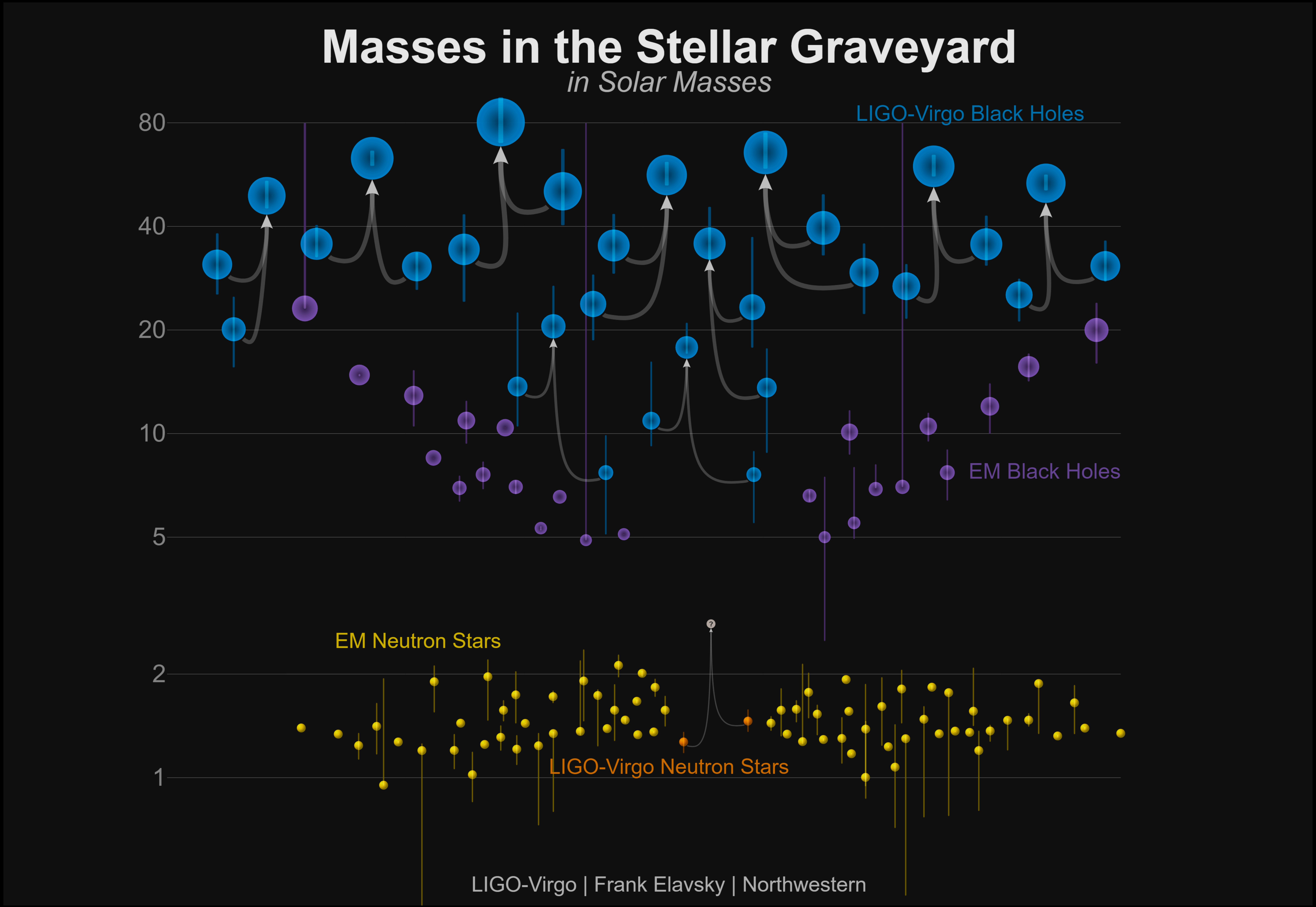
-100 -50 0 50
t-t_c (s)
10^{-2} 10^{-1} 10^{0} 10^{1}
t-t_c (days)
1M2H Swope
10.86h
i
DLT40
11.08h
h
VISTA
11.24h
YJK_s
Chandra
9d
X-ray
MASTER
11.31h
W
DECam
11.40h
iz
Las Cumbres
11.57h
w
J VLA
16.4d
Radio


Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
?
LIGO-Virgo | Frank Elavsky | Northwestern